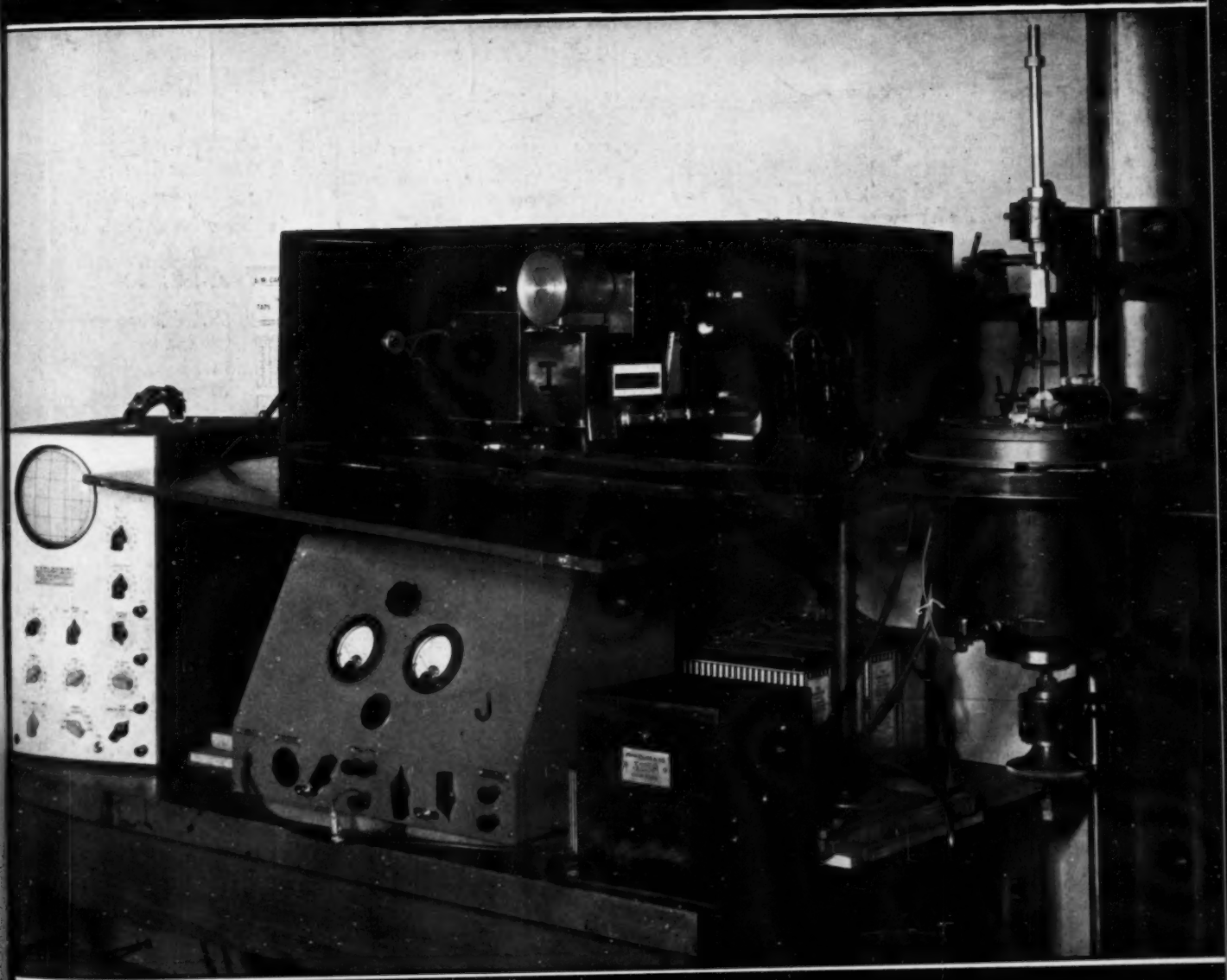
JOURNAL OF APPLIED PHYSICS



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Maintaining the Supply of Physicists

"One of the greatest resources in the arsenal of Democracy is our national ability and interest in Industrial Research. For the vigorous prosecution of our defense program and for the assurance of national progress after the emergency we rely heavily on the continued vitality of research by industry in both pure and applied science. . . ."

FRANKLIN D. ROOSEVELT

"I wish to urge the immediate expansion of our research facilities in pure and applied science and the more systematic application of what we already know in these fields. This is the more urgent today because through it we can help alleviate the hardships of our people during and after this war. . . ."

HERBERT HOOVER

A CAREFUL reading of these quotations from two men of opposing political philosophies brings out a striking similarity in purpose. Each emphasizes the need for scientific research in the present emergency. There is, however, a second point stressed in each of these quotations—the need for scientific research for "national progress after the emergency." It is with this second point that we are concerned in this brief editorial note.

In an emergency such as the present one, we all realize that it is unavoidable that physicists in industrial laboratories have had to give up research upon what one might call "company problems" in favor of defense problems. It is unavoidable that physicists have been drafted in alarmingly large numbers from universities and that, as a result, teaching programs and pure science research programs have been greatly curtailed. Although unavoidable, these facts and the difficulties they raise should not be minimized. Whether or not the war continues for a long time, an increasing number of new physicists will be needed. The responsibility exists, therefore, for physicists as a group to develop a plan whereby in spite of the depletion of many university staffs, training of new physicists will proceed at a rate at least as large as before the emergency.

It would be presumptuous to recommend a definite plan here. The formulation of an adequate plan requires much thought and thorough discussion. It seems essential that more and better students be led into physics both in high school and in the early college years. Perhaps the establishment of roving lectureships would spread the contagious enthusiasm of a few of our outstanding leaders over a much greater audience. Perhaps radio programs or science exhibits would help arouse interest among students. A second requirement of any comprehensive program to maintain the supply of well-trained physicists in spite of depleted staffs seems to be a critical analysis of the value of each course in the curriculum. Basic courses in mechanics, heat, sound, electricity, electronics and optics should be expanded at the expense of "frills." Courses should include more problem solving and less lecturing. It seems that some plan should be worked out to give students a better opportunity to carry on research especially at those institutions whose research leaders are on leave. Perhaps, defense research carried on away from the institution giving the degree could be counted as part of the thesis requirement. These are only a few of the questions that need to be thrashed out. It is the purpose of this note to recommend that a group be called together in the near future to consider seriously what may be done to insure a continuing supply of well-trained young physicists.

The Role of Physics in Dentistry

BY ARTHUR B. GABEL

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THE scope of the application of the principles of physics to dentistry is not widely recognized. The purpose of this paper is to outline some of the more fundamental dental problems to which physical principles may be applied and to show what progress dentistry has made in their application.

Before going into the more specific problems let us consider the masticatory apparatus as a whole. In the main it consists of two parts, one fixed, the other movable, the upper and lower jaws or maxilla and mandible, respectively. The lower jaw is U-shaped with the ends of the U turned upward. The posterior parts of these ends terminate in elongated knobs, called condyles, with their axes nearly perpendicular to the median plane but usually pointing slightly backwards. The upper surfaces of these elongated knobs form part of the articulation with the skull but a movable disk of cartilage is interposed between the bone surfaces (Fig. 1). Each joint is a sliding hinge. When the mouth is merely opened the horizontal axis moves forward and down (Fig. 2) onto a prominence on the articulating surface of the skull. For incising, the jaw may be thrust straight forward, but in ordinary chewing it swings to the side during the opening movement and as it clamps down on the bolus of food swings back to the center position with a resultant crushing and shearing action on the bolus. During movement, in addition to the rotation about a horizontal axis, there is also a rotation about a nearly vertical axis which may lie completely outside of the head.

The discussion so far has ignored the fact that the movements of the lower jaw are influenced by the antagonistic tooth surfaces. The highest points of the teeth of each jaw, when in contact, lie approximately in a surface called the occlusal plane (Fig. 3). This is not actually a plane but a surface curving anteroposteriorly and also laterally. It has even been described as spherical. In addition there are the inclined surfaces of the cusps and ridges of the individual teeth to be considered.

It is probable that, in the normal case, the resulting arrangement of the small inclined surfaces of the opposing teeth are of far greater importance in determining mandibular movement when the teeth are in contact or separated by a thin layer of food than are the joints.

It can be seen that the movements of the mandible are complicated and varied. In the normal case the tooth surfaces in contact are so coordinated that any customary movement can be executed smoothly and without putting any undue strain on individual teeth, their supporting tissues, or any parts of the mandibular joints. When, however, one or more of these parts is not properly coordinated, normal movement is interfered with and some part of the apparatus is subjected to a stress which nature has not designed it to withstand without injury. This constitutes one of the major problems in dentistry.

FIG. 1. Portion of a skull showing the mandible in its normal resting relationship. Disk of cartilage not shown.

Dentists have been unable to carry out the complicated technique of replacing lost teeth by working directly on the patient. It is necessary to make casts of the surfaces of the jaws which will

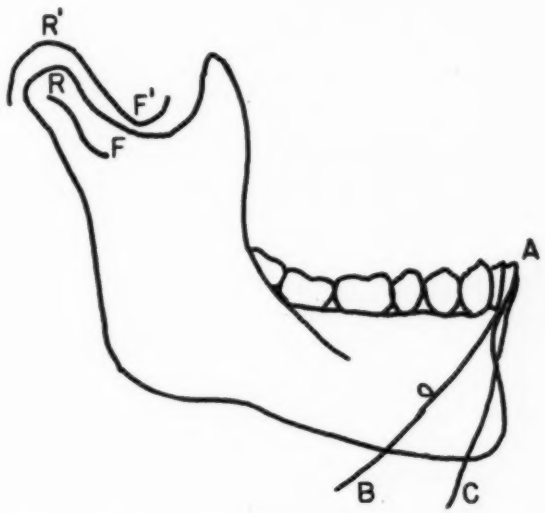

FIG. 2. Diagram showing path of mandible in simple opening and closing. In pure rotation A moves along AB; but in real movement A moves along AC, while condyle axis moves along RF parallel to $R'F'$.

bear these replacements and to mount these casts in their correct relationship on a mechanism, called an articulator, which attempts to duplicate the movements of the lower jaw. Some of these devices and the registrations and adjustments required are quite complicated, yet, about the best any of them will do is to produce a forward, a right, and a left movement from the rest position. The end points are accurately registered but the paths by which they are reached are purely arbitrary. In spite of these shortcomings the result may be decidedly satisfactory, first, because the actual working movement of the mandible is only a few millimeters and so the deviation from the true path can be only slight, and second, because the yield of the soft tissues will permit of a slight departure from this path. In addition, clinical experience seems to indicate that the dental mechanism has considerable ability to accommodate.

The analytical treatment of mandibular movement would in all likelihood be unnecessary and also too complicated for general practical use. However, a fundamental knowledge of the principles of a general solid displacement of a rigid body would undoubtedly be of benefit in certain unusual types of cases and in a pure study of mandibular movements.

The problems involved in construction aside from the kinematical one of determining the displacements of the mandible are entirely those of statics. They are concerned only with maintaining a state of equilibrium at all points within the working range of the mandible, between the force of mastication, the reacting forces at the points of support, the pull of sticky foods, and the force of gravity acting on appliances in the upper jaw.

The partial prosthetic appliance, or so-called partial plate, partly tooth supported and partly soft tissue supported, offers the greatest problem to the average dentist. Lacking a knowledge of mechanics he usually tries to type these according to some scheme proposed by a practitioner who has had a higher degree of success, usually through a better basic understanding of the problem.

The forces previously mentioned, that is, masticatory, supporting gravitational, and those resulting from sticky foods, are the only ones applied and are practically parallel, thus simplifying the mechanical considerations from the standpoint of the stability of the appliance.

However, these appliances are usually attached to the supporting teeth by devices, taking advantage of undercuts or friction so as to resist small displacing forces opposite in direction to those of mastication. Where the supporting teeth

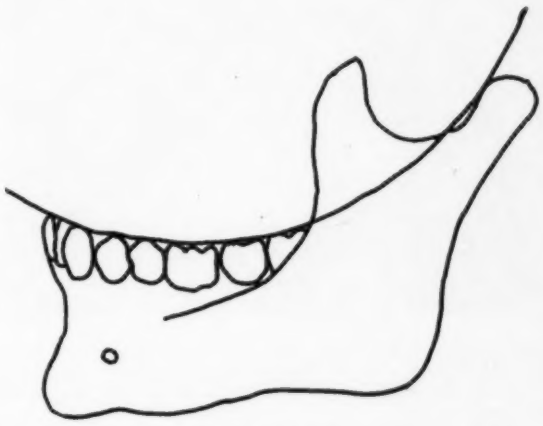

FIG. 3. Diagram of mandible showing anteroposterior curvature.

are distributed so as to be able to carry the whole load the difficulties are not great. But, where part of the support must be furnished by gum tissue, another factor comes in. Since there may be more yield to the gum tissue support than to the tooth support, torques which eventually result in injury to the tissues supporting the abutment teeth are produced. Failure to overcome these torques has resulted in the loss of many sound and useful teeth.

In order to overcome this effect, several years ago the writer designed a clasp with a hinged joint (Fig. 4) which permits the supporting tooth to carry its full vertical load but does not permit any torque[1] to be transmitted to it as a result of compression of the gum tissue. So far this design has been applied to the lower jaw only. There are certain technical difficulties encountered in applying it to the upper. Besides it is not quite so necessary here because of the larger soft-tissue bearing area on the hard palate.

The displacement of the individual tooth under various loadings and the means of its support present an interesting and important problem.

The tooth root is not in immediate contact with its bony socket but is separated by a membrane, the dental periosteum, roughly 1/100 of an inch thick. This thickness varies over different parts of the root, being greatest where the displacement is greatest. Running through this membrane are tough fibers, one end of which

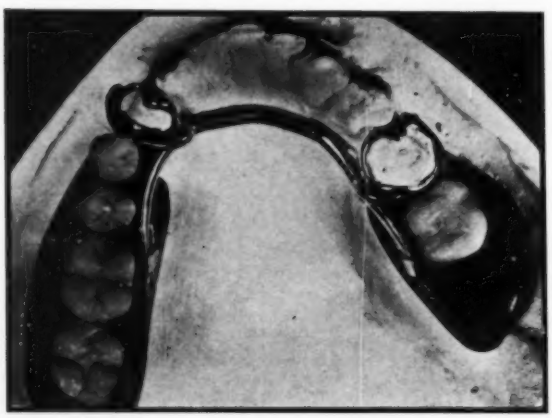

FIG. 4. Partial plate with hinged clasps to remove torque. Hinge axis is placed over estimated rotation center of tooth. Bar-end in box permits only one degree of freedom.

[1] Arthur B. Gabel, "A non-torque clasp," J. Dent. Research **14**, 457 (1934).

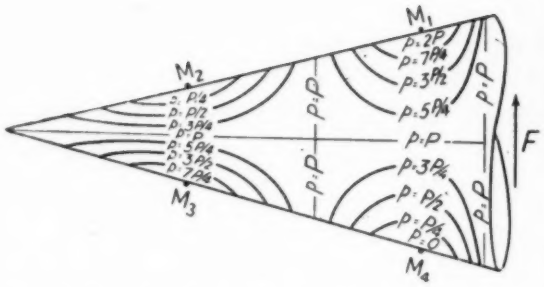

FIG. 5. Synge's calculations of pressures p in terms of atmospheres P set up in the membrane of a conical root by a transverse force F. Points M are those of maximum and minimum pressures.

is imbedded in the bone of the socket wall and the other in the root. These fibers have a more or less definite arrangement and direction in different parts of the membrane. This fact has led most investigators to assume that they resist the forces which tend to displace the tooth during function. There are several conditions which cast doubt on this assumption. First, as seen in microscopic section, these fibers usually are not straight and none runs parallel to the long axis of the tooth except at the apex. Second, a tooth with a healthy membrane suffers an extremely small displacement even under considerable load. Third, a tooth with a slightly inflamed and congested membrane suffers considerable displacement under a comparatively light load.

Several years ago a new theory of tooth support was presented before the Royal Society of London[2] by Synge, a mathematician, at the instigation of Box, a dental investigator, as a result of the latter's investigations of the cause of disease of the dental periosteum. Starting with a few clinically and histologically established facts he assumed that the dental periosteum acted as a thin elastic membrane incompressible because of its vascularity. The modulus of compression, being infinite, the strain in the membrane can be infinitesimal even though the modulus of rigidity is finite. The fact that the membrane is probably anisotropic was not considered and the general problem gave results mathematically the same as those first given by Reynolds in connection with the theory of lubrication (Fig. 5).

[2] John L. Synge, "The tightness of the teeth, considered as a problem concerning the equilibrium of a thin incompressible elastic membrane," Trans. Roy. Soc. **A231**, 435–477.

This theory not only explains the almost infinitesimal displacement of the tooth under finite load, but also the great increase in this displacement with increase in thickness of the membrane since the displacement varies as the cube of the thickness. In addition, the location of the center of rotation of the tooth under transverse load, a matter of great importance to dentistry, was found to be in fair agreement with the findings of Schwarz[3] in experiments on dogs.

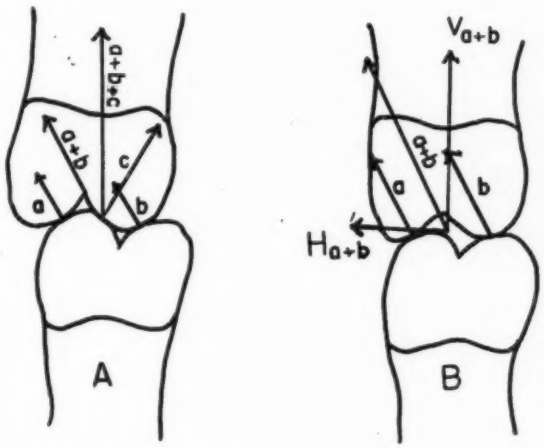

FIG. 6. Diagram showing cusp relationships and forces in (A) center or resting position and (B) lateral or working position.

The effect on the supporting structure of the transverse loading of the coronal end of a tooth is obviously the same as that produced in the case of teeth supporting tooth and soft tissue borne appliances. However, it is more universal because it may occur in complete natural dentures even where no type of restorative work has been done.

It was mentioned previously that the inclined surfaces of the cusps and ridges are largely responsible for guiding mandibular movement. It should be noted that these inclined surfaces are not actually planes but curved surfaces. However, as we are dealing with equilibrium states at various points of contact we may treat them as planes with a slope equal to the slope of a tangent at the point of contact.

When the jaws are merely clamped shut, which is the center position at the end of a masticating stroke previously referred to, in the normal arrangement of these inclines (Fig. 6A), an approximation to balance is maintained between opposing transverse forces, but when, for any reason, there is a disturbance of this arrangement, this balance is destroyed. In the working relationships, i.e., when the lower jaw is lateral to the above position so that opposing cusps meet almost end to end (Fig. 6B), the transverse forces do not, in the normal case, overload the supporting structures; but if the inclines are too steep, or, especially, if this steepness is confined to one or two teeth, the load is increased beyond the ability of these structures to bear it.

Fortunately, nature comes to our assistance by reducing the angle of inclination with age, which compensates for the resorption of the supporting bone. Friction also plays a role in reducing the effective angle. The coefficient of friction between tooth surfaces, to the best of my knowledge, was never measured until it was done recently by two groups of our students.

The inclined plane also plays an important part in a consideration of the mechanics of one particular type of restoration, or so-called "filling." In this type, the decay involves the surface of a posterior tooth where it is in contact with a neighboring tooth. Whether or not the biting or occlusal surface is involved it must be penetrated to gain access to the decay. The wedging action of opposing cusps (Fig. 7) between inclines on the restored and original portions of the occlusal surface tends to displace the restoration.

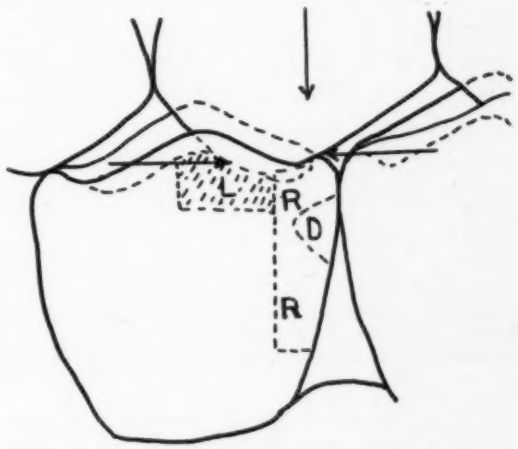

FIG. 7. Diagram showing wedging action of opposing cusp between fillng without dovetail and tooth. *D*, outline of original decay; *R*, restoration without lock; *L*, lock.

[3] A. M. Schwarz, Kopfhaltung und Kiefer, Zachr. F. Stom. 1926, H. 8.

The retention of this type of restoration (Fig. 8) offers interesting mechanical problems. The writer has made calculations which seem to indicate[4] that with the type of retention originally used, parts of the tooth structure might conceivably be subjected to compression forces of over 30,000 pounds per square inch. Due to the many failures, retention is now obtained by a dove-tailed lock on the biting surface of the tooth thus reducing these compressive stresses to zero.

This same type of restoration also offers an interesting problem in retention based on the relative rigidities of the tooth structure and the restorative material.[5]

Space permits a discussion of only a few of the major problems of dentistry calling for the application of mechanical principles. There are many others, such as the substitution of mechanical for anatomical tooth forms on artificial dentures,[6] and the mechanics involved in bridgework.[7]

Turning to the esthetic side of dentistry, the problem of matching color with porcelains and cements is seldom easy and is often almost impossible. In the past it has been treated entirely empirically, but in recent years an increasing number of practitioners has been applying a knowledge of the principles governing color production and the effect of the quality of the incident light.[8]

A restoration placed beside natural teeth may be seen in cold blue north light or the warm yellow light of a candle. This is a range of color temperature from about 25,000°K to 1900°K. Since, with the materials now available, teeth can be matched accurately at only one color temperature, judgment and an understanding of the principles involved are required for a satisfactory result.

The so-called daylight lamp of the filter type has found some use in the laboratory. However, the high wattage required to offset the loss of luminosity due to filter absorption has resulted in too much heat for use on the patient. The advent of the new fluorescent tube and the efforts of the manufacturer of dental equipment to produce a lamp to give a predetermined color temperature will, no doubt, solve that problem in the near future.

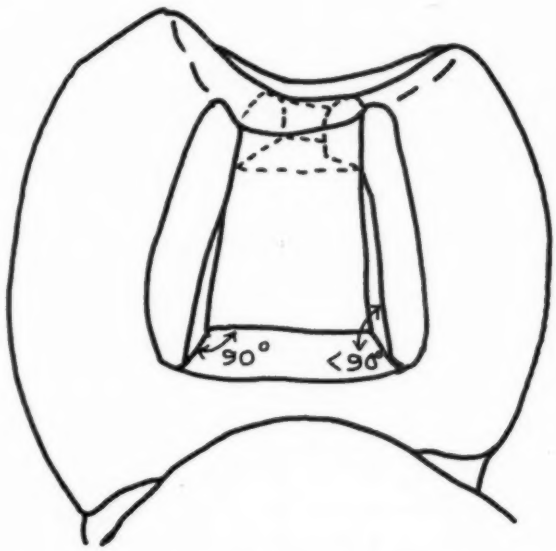

FIG. 8. Side view of tooth in preceding figure showing cavity preparation without and with lock.

The application of polarized light, by means of the photoelastic effect, to a study of the strains produced in various types of dental restorations holds out promise of fruitful results.[5] However, polarized light is not new to dentistry but was used years ago in studies of normal enamel with the polarizing microscope. Changes in birefringence under various conditions were noted and theories proposed. By these studies the uniaxial form of the enamel crystal was determined.[9]

Later the x-ray was used to make densitometric studies[10] of normal and pathologically altered enamel and dentin in different parts of the tooth. Recently x-ray diffraction methods have been

[4] Arthur B. Gabel, "Mechanical principles involved in the class II restoration," Dental Cosmos **78**, 1021 (1936).
[5] Arthur B. Gabel, "Operative procedure, etc.," *American Text-book of Operative Dentistry* (M. L. Ward, Editor) (Lea and Febiger, Philadelphia, 1940), seventh edition, Chapter VIII, p. 238.
[6] Clyde H. Schuyler, "Selection and modification of posterior tooth forms, etc.," Oral Health **24**, 47 (1934).
[7] Stanley D. Tylman, *Theory and Practice of Crown and Bridge Prosthesis* (The C. V. Mosby Company, 1940).
[8] E. Bruce Clark, "The color problem in dentistry," Dent. Digest, **37** (1931).
[9] W. J. Schmidt, *Handbuch der biologischen Arbeitsmethoden* (Abderhalden, 1934), Section 5, Part 10, p. 435.
[10] G. Van Huysen, Harold C. Hodge and Stafford L. Warren, "A quantitative roentgen-densitometric study of changes in teeth due to attrition," J. Dent. Research **16**, 243 (1937).

used in the study[11] of enamel which has been found to be isomorphous with apatite. The x-ray has, so far, not been of any therapeutic value in dentistry.

Ultraviolet light has been used therapeutically but with uncertain results. The therapeutist generally has not known that ultraviolet light extends over a range of nearly 4000 angstrom units and the effect of energy and wave-length on the micro-organisms and on the tissues of the host has not been well understood.

Ultraviolet light is finding some use in photomicrography where extreme resolving power is necessary. However, the new electron microscope will probably supersede all optical instruments for these cases.

Going beyond the other end of the visible spectrum, dentistry, unlike medicine, finds no real use at present for the infra-red radiations. However, the part played by that closely related form of energy, heat, should be mentioned. The use of metal for restoring tooth structure has centered considerable attention on thermal conductivity and expansion. Shrinkage of cast inlays from the fusing temperature to that of the mouth was for years a difficult problem. It was overcome by developing materials for the mold which gave an expansion curve which flattened out considerably near the proper percentage expansion. In the past, the temperature of the mold was judged approximately by the color, but recently the thermocouple type of pyrometer has been coming into use. The differential thermal coefficient of expansion of some dental materials and tooth structure is quite large and an understanding of this fact is often of clinical importance.

The theoretical knowledge of heat which finds use in dentistry is very limited. At present there appears to be no need for the clinician or the investigator to understand reversible cycles or entropy. However, a fuller appreciation of the meaning of the first law of thermodynamics might gain the former the eternal blessing of some hypersensitive patient.

No discussion of the role of physics in dentistry would be complete without reference to the part played by electricity. It is used for the direct production of heat in accordance with Joule's law and makes possible bloodless surgery by means of the electrocautery. Or, it may accomplish the same end through surgical endothermy by generating high frequency currents in an oscillating circuit. Again, it may be used to carry the active ion of a drug into the deeper tissues. The intelligent use of these tools is a boon to mankind but ignorance of the laws governing their operation may result in at least unpleasant incidents as, for example, the shock a patient may receive due to self-induction if the operator removes the electrode of a cataphoresis machine before opening the switch. It cannot be expected that the dentist be well versed in electrical theory, but he should, so to speak, understand Lenz's law and Faraday's rule and what their implications are.

Dentistry does not part from physics at this point but with it takes the last step into the subatomic world. It is already using one of physics' most recent contributions to science, artificial radioactivity. Studies of phosphorus metabolism[12] of the teeth of laboratory animals and man have been made with sodium phosphate containing radioactive phosphorus.

Dentistry has made much use of physics, accepting what it could turn to its own benefit. Some of these gifts it has applied directly to the prosecution of its art; some it has used as keys to new stores of knowledge. In closing, one more debt to physics must be acknowledged. No field of human endeavor contributes more to straight thinking and mental discipline or does more to develop the scientific attitude. And these, regardless of the material to which they are applied, are necessary for the full development of the individual and the advancement of the field in which he works.

[11] J. Thewlis, "The structure of tooth enamel," Brit. J. Radiol. [New Series No. 101], **9**, (May, 1936).

[12] A. Krogh, J. G. Holst, and G. Henesy, "Investigation of the exchange of phosphorus in teeth using radioactive phosphorus as indicator," Det. Kgl. Danske Vid. Selskab., Biol.-Med. **13**, 13 (1937).

Frictional Phenomena. III

BY ANDREW GEMANT
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Chapter III. Absorption of Sound Waves and of Supersonics

Abstract

THE extent to which viscous processes can account for the absorption of freely traveling acoustical waves in gases is shown. Considerable divergence between theory and experimental data is found for polyatomic gases, and an explanation of this divergence on the basis of intramolecular vibrations is presented.

12. Theory of Absorption Due to Viscosity

Applications of viscous processes in gases lie to a large extent in the field of acoustics, with which, accordingly, we shall be concerned in the following two chapters.

Some experimental devices considered in the previous chapters made it clear that the viscous forces constitute a sort of resistance in channels and tubes. This resistance can be defined by Eq. (13) which is completely analogous to Ohm's law in electrical circuits. This resistance then has the value given by (11e) for parallel walls, or by

$$R=8\eta/\pi a^4 \qquad (28)$$

for a cylindrical tube of unit length, according to Eq. (27). The result, as already shown, is a dissipation of energy as heat.

In case the gas does not flow in a stationary manner but performs an oscillatory motion, we have to deal with acoustical waves. It can be assumed that viscous forces again will play an important role, even if the manifestation is markedly different from that in stationary processes. They will have one feature in common, and this is the dissipation of energy in the form of heat.

If acoustical oscillations are generated at a certain point in a gas, waves will propagate in certain directions, chiefly controlled by the shape of the generator and the existing solid boundaries. If the space is relatively large, spherical waves will be generated; if the gas is confined to the interior of a rigid tube, or if the generator is a large plane membrane, the waves will propagate chiefly in one direction, and are called plane waves. Conditions are particularly simple in this latter case, and since they occur in a number of practical cases (at least to a high degree of approximation), they should be considered here in more detail.

The intensity at the origin should be assumed as constant, which is the case if the amplitude of the generator is maintained at a given level. Let us assume that the wave is strictly a plane one, then no widening of the wave front takes place in moving further away from the source. In this case the intensity of the wave should remain constant with increasing distance from the source, were it not for the viscous forces in the gas causing a transfer of the kinetic energy into heat. The result will be what is called an attenuation of the wave, the latter occurring, according to experience, exponentially, as in the case of electrical waves. Denoting the exponential factor by which the amplitude has to be multiplied by $e^{-\alpha x}$, where x=distance from the source, the attentuation factor α has been introduced. This factor is a function of the viscosity of the gas, and this relation will now be deduced. By making use of the general equations dealt with in Chapter I, this can be done easily.

Equation (8) can be used directly in this case, since the direction of propagation was taken to be the x axis, and the nature of acoustical waves is known to be longitudinal, oscillation of the particles taking place in the direction of propagation, that is, in the x axis.

There are no volume forces acting on the gas, so $F_x=0$. The inertia component $-\rho\partial u/\partial t$ has to be retained. The stress components X_x . . . are given by Eqs. (3). Here we note that the x gradient of the pressure p enters the equation. This term has a special significance. Apart from the inertia term, it is the only one that does not contain the viscosity as a factor. We have seen in the stationary cases that a finite pressure

difference was acting and that this represented the actual driving force. In acoustical waves there is no finite pressure difference. There are only infinitesimal pressure differences between neighboring volume elements owing to the fact that the longitudinal to and fro motion of the molecules causes periodical compressions and expansions. These local pressure differences are of the nature of elastic forces which, together with the inertia, maintain the wave motion. They correspond to the potential and kinetic energy of the system. To these two are then added the viscous or dissipative forces.

The inertia term and the viscous term of Eq. (8) operate with the velocity u as the dependent variable; the pressure term, therefore, has to be reduced to the same variable. This happens by introducing a quantity called condensation s according to the definition

$$\rho=\rho_0(1+s), \tag{29}$$

s being the relative change in density due to the oscillation of the molecules. In applying the gas law, the pressure must always be proportional to the density, thus we can write

$$dp=a^2\rho_0 ds, \tag{30}$$

where a^2 is a positive constant to be determined from the gas laws. Equation (30) connects the pressure with the condensation, and the latter is related to the velocity by means of the so-called continuity equation:

$$\partial s/\partial t=-\partial u/\partial x, \tag{31}$$

expressing the evident fact that the density can change with time only, if there is a finite divergence of the velocity. If the velocity decreases with increasing x, more material will enter the volume element dx than will leave it, and the density must increase.

Before replacing p by u, let us write down Eq. (8), valid for our special case. In using Eq. (3) for the stress components, and considering that only X_x is different from 0, we obtain

$$\rho_0\frac{\partial u}{\partial t}+\frac{\partial p}{\partial x}-\frac{4}{3}\eta\frac{\partial^2 u}{\partial x^2}=0. \tag{32}$$

In order to substitute u for p according to Eqs. (30) and (31), first (32) has to be differentiated with respect to time, and we obtain in this way the partial differential equation:

$$\frac{\partial^2 u}{\partial t^2}-a^2\frac{\partial^2 u}{\partial x^2}-\frac{4\eta}{3\rho_0}\frac{\partial^3 u}{\partial^2 x\cdot\partial t}=0. \tag{33}$$

The solution of this equation is given by the equation of a progressing sine or cosine wave, and in writing down the solution, and substituting it into (33), the damping factor α is directly obtained as a function of the viscosity, which was the purpose of this derivation. Thus, we write for the solution:

$$u=Ae^{-\alpha x}\cos 2\pi\nu(t-x/c). \tag{34}$$

In this equation A is the amplitude of the oscillating velocity, α the damping factor, mentioned above, ν the frequency of the oscillation, and c the propagation velocity of the wave (not to be confused with its meaning in Chapter II). In putting (34) into (33) it will be seen that (33) is identically correct if the two conditions hold:

$$c=a \tag{35}$$

and

$$\alpha=8\pi^2\nu^2\eta/3\rho c^3, \tag{36}$$

in dropping the index of ρ. The first of these allows the propagation velocity c to be computed from the gas laws, and the second is the answer to our special question concerned with the viscosity. As to the first point, it should be recalled that the compression and expansion of the gas occur so fast that there is no time for a thermal equilibrium to be established between neighboring volume elements: in other words, the process is an adiabatic one. Using the gas laws for this case, one obtains

$$c=(\kappa p_0/\rho)^{\frac{1}{2}}, \tag{37}$$

where p_0 = atmospheric pressure and κ = ratio of specific heats: c_p for constant pressure, and c_v for constant volume. With $\kappa=1.40$ for air at zero C, the equation yields the value 332 m/sec. for the velocity. It then follows from (36) that the attenuation factor is proportional to the ratio viscosity over density (called kinematic viscosity) and to the square of the frequency of the oscillation. Applied to sound waves this means that the absorption of freely traveling

waves increases with the second power of the pitch of the sound.

In discussing the experimental check of Eq. (36), a further point has to be added. Because of the adiabatic nature of the local compressions, the temperature will rise above that of the surroundings and, since the process has a finite velocity, a little deviation from the purely adiabatic condition will take place, resulting in a beginning equalization of temperature. This again is an irreversible process, and leads to further dissipation of energy. The attenuation due to this mechanism was computed by Kirchhoff, and the formula obtained is similar to Eq. (36). The sum of both, α' is given by:

$$\alpha' = (2\pi^2\nu^2/\rho c^3)(4\eta/3 + [\kappa - 1]k/c_p), \quad (36a)$$

where c_p = specific heat at constant pressure and k = heat conductivity of the gas.

13. *Experimental Data*

In turning to experimental data, a few words regarding the methods of measurement will be of interest. Abello[1] used a piezo-quartz crystal as a sound emitter which, as is known, is useful for supersonic frequencies, and a cylindrical tube, filled with the gas in question, thus providing a path for the traveling waves. At the end of the tube a second piezo-quartz, coupled with an electronic voltmeter, registered the intensity. The ratio of output to input at the ends of the tube measures the absorption. Pielemeier[2] made use of the so-called "supersonic interferometer" devised by Pierce. A quartz or magnetostrictive generator, connected to an electrical oscillator is used, and standing waves are produced by means of a reflecting wall parallel to the generator surface. The reaction of the reflected wave upon the generator is measured by changes of the anode current passing through the oscillator tube. After a suitable calibration the diminution of the intensity of the waves because of absorption can be found. Most interferometers operate with a variable path between reflector and generator; a constant path interferometer in which the gas pressure is varied is described by Herget.[3] Hubbard and Zartman[4] also describe the fixed path instrument, and give results on air and carbon dioxide.

Grossmann[5] uses the basis of a longitudinally vibrating quartz rod as a "point" of source of the waves. The traveling waves are approximately spherical in such a case, and in measuring the intensity at distances r from the source, one can find the deviation from the $1/r^2$ function. Thus the absorption in the particular gas is found.

Knudsen[6] makes use of the reverberation time (see Chapter IV) of an enclosure, which is a function of the total absorption. The latter is caused partly by the walls, partly by the gaseous medium. By using enclosures of different sizes it is possible to differentiate between the two components, and thus determine the absorption coefficient of the gas.

A recent and interesting method makes use of the fact that standing acoustical waves act as diffraction grating for light. Diffraction patterns of the light are thus obtained, the intensity of which is a measure of the sound intensity. A detailed discussion of this method, developed independently by Debye and Sears[7] and by Lucas and Biquard,[8] cannot be given here; compare a recent paper by Petersen.[9]

Let us now see the actual figures in certain instances, as compiled by Bergmann.[10] The following table gives the gas, the frequency range and coefficients as computed with Eq. (36a) and determined by the respective authors. The coefficient is given as α'/ν^2, a usual sort of notation.

TABLE II. *Sound absorption coefficients of different gases.*

Gas	Frequency Range in Kilocycles	α'/ν^2 in 10^{-12} Absolute Units: Calculated with Eq. (36a)	α'/ν^2 in 10^{-12} Absolute Units: Experimental	Author
Air	178	0.145	0.27	Grossmann
Air	1160–1410	0.145	0.17–0.29	Pielemeier
Argon	612	0.20	0.	Abello
Carbon Dioxide	64	0.160	27.7	Grossmann
Carbon Dioxide	99	0.160	54.0	Grossmann
Carbon Dioxide	178	0.160	24.0	Grossmann
Oxygen	655–1220	0.178	0.35–0.19	Pielemeier

With the exception of the result obtained for argon, one sees that the measured coefficients are higher than the calculated values. Whereas there is an agreement as to the order of magnitude for air and oxygen, a considerable divergence exists

for carbon dioxide and, it should be added, for other, particularly polyatomic, molecules as well. It follows from this that in a number of cases absorption is caused by a mechanism entirely different from that hitherto considered.

Now, if we wanted to proceed on a more restricted basis, this is what should be said: This monograph is concerned with viscous processes, using the conception that a viscous force in gases is due to a transfer of momentum from a faster moving layer to a slower moving one. We now see that the absorption of sound waves, particularly in the supersonic range, is only partly due to this mechanism; partly, and in some cases to a much larger extent, however, to some quite different cause. This second mechanism is outside of the scope of this discussion.

We intend, however, to deviate from this narrow viewpoint for the following reason. It was shown that the most important feature of viscous processes is the transformation of ordered kinetic and potential energy into heat. This is the feature that is directly accessible for measurements also. We refer to this transformation, shortly, as loss. Viewed from this somewhat wider angle, it can be said that the losses along supersonic waves are only partly of a viscous nature; they are due in part to a different cause. But since both lead to the same kind of losses, the consideration of the second mechanism is well worth inclusion in our discussion.

14. Absorption Due to Molecular Vibrations

Keeping the above in mind, a brief discussion of this particular mechanism is to follow. In order to give a possibly simple presentation, let us first consider a so-called ideal wave, one without any loss. Let us select a small volume of the gas in the path of the wave and consider the periodic pressure and volume changes in that volume element. According to the process described in Section 12, the element in question will be periodically compressed and expanded. High pressure coincides with small volume and vice versa. In Fig. 11 the lower sine curve is the pressure variation curve, the upper curve, 1, the volume variation, the abscissa being the time.

The work done by the wave on the volume element is for a small change dv given by $-pdv$ and for a finite time $-\int pdv$. It can be seen that during the period a–b–c the wave will perform a certain work, and during the period c–d–e the volume will return the same amount to the wave; thus the balance is zero. The wave does not lose any energy. Thus, there is no absorption present. Condition for this situation: volume and pressure have a phase difference of 180° or, in other words, pressure and density are in phase.

Consider now a volume element that—for whatever reason—absorbs all the energy of the wave. The volume curve is then given by curve 2, Fig. 11. Taking again a whole period, it is seen

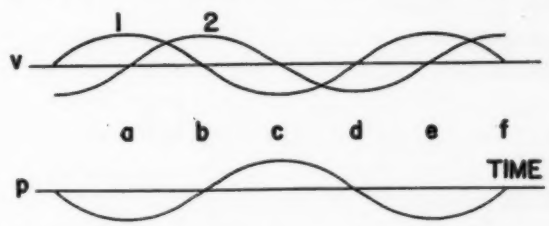

FIG. 11. Diagram of volume and pressure curves for traveling sound waves in non-absorbing and highly absorbing gas.

that during b–c–d work is done by the wave against high pressure; during d–e–f work is returned at low pressures, the balance being positive. The wave continuously works on the volume element, and the corresponding energy is lost as heat. Condition for maximum absorption: the pressure and the volume (or the density) are 90° out of phase. Or, in other words, pressure gradient and deformation velocity are in phase.

The nature of the actual force that is opposed by this pressure gradient is different according to the nature of the absorption process. If the latter is caused solely by the viscosity—think of an imaginary gas of extremely high viscosity—then it is the viscous force that must be overcome by the wave pressure.

If, now, a large component of Type 1 is added to a small component of Type 2, corresponding to actual cases with a small fraction of absorption, a curve will result which is situated like 1, but shifted to the right by a small angle, the so-called loss angle. Condition for small, but finite absorption: the density lags behind the pressure by a small angle.

This consideration, based on the phase angle between pressure and volume, is very fruitful in

that it immediately explains the presence of losses whenever a phase shift between pressure and density can be found by any mechanism—even one entirely different from viscosity.

Such a mechanism for polyatomic gases has been found by Kneser,[11,12] and, in showing that it leads to a phase shift between pressure and volume, he establishes also the occurrence of absorption. The process in question is based upon the vibrational energy of atoms within molecules. We know (Section 8) that the pressure in gases is determined by the velocity of the translational motion of molecules. Besides this translational (and rotational) motion the vibrational degrees of freedom have also to be considered. There is a continuous exchange of energy between the different degrees of freedom according to the equipartition principle.

The exchange between rotational and vibrational energy is not momentary; it requires a small, but finite, time, depending upon the average life of normal and excited molecules (those without and those with vibrational energy quantums). The longer the average life, the longer time it takes for the exchange to be completed. This time should be denoted by τ.

If a gas volume is compressed, the external work done is transformed into heat, thus raising temperature and pressure. The kinetic energy

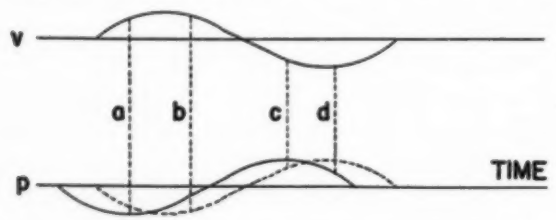

FIG. 12. Diagram of volume and pressure of sound waves in gases exhibiting intramolecular vibrations.

of the molecules in the first moment is purely translational. An exchange of part of the translational energy into vibrational energy will start immediately, and will be finished after a time of the duration of a few times τ. The initial state will pass into an equilibrium after a time τ, for which reason τ is called a relaxation time. During this process of relaxation the pressure will drop slightly, because part of the translational energy responsible for the pressure is converted into vibrational energy.

The result of this relaxation is shown schematically in Fig. 12, indicating the volume and, below (dotted line), the pressure curve of a gas without losses. Now consider the intervals a–b and c–d, during which the sine curves are in first approximation constant. Because of the adjustment in pressure just explained, the full lines will indicate the real behavior of the gas pressure. It can be seen that, in completing these portions, a

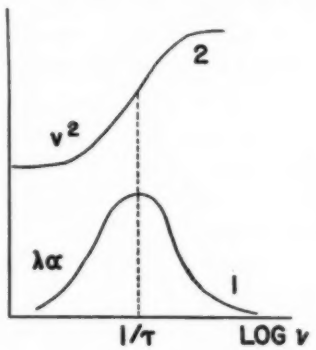

FIG. 13. Absorption and dispersion of sound waves in polyatomic gases as a function of frequency.

sine curve will result that is slightly phase-shifted against the volume curve. According to the statements made above, this is identical with an absorption of acoustical waves in the gas.

A recent discussion of the phase difference as caused by molecular absorption is given by Namoto.[13]

A more detailed theory allows the computation of the absorption as a function of frequency. Figure 13, curve 1, shows the product $\alpha\lambda$ (λ = wave-length) as a function of the logarithm of the frequency. The product $\alpha\lambda$ is equal to $\pi \tan \varphi$, if φ is the phase shift angle between pressure and density. It can be seen that for low and high frequencies α is zero. In these ranges absorption is controlled chiefly by the viscosity. At a given frequency of the order $1/\tau$ absorption has a maximum. The reason for the special shape of the $\alpha\lambda$ curve is roughly as follows. For periods much larger than τ, equilibrium between normal and excited molecules is established so fast and the interval a–b (Fig. 12) is so small that the phase shift becomes negligible. For periods much smaller than τ, on the other hand, excited molecules are not generated at all, the whole mechanism, so to speak, ceases to function, and naturally, again, no absorption occurs. Only in the range where the period of the wave is comparable with τ is the absorption finite.

Curve 2, Fig. 13, shows that the wave velocity v reaches a higher value with increasing frequency in the same frequency range $1/\tau$ where absorption occurs. This is called the sound dispersion, and has the same reason as the absorption. This is seen directly from Eq. (37) where κ, as stated, is equal to c_p/v_v. Since $c_p - c_v = R$ (R = molar gas constant, not to be confused with R used for resistance as in Eq. (28)), we have

$$v = [(p_0/\rho)(1 + R/[c_{vt} + c_{vv}])]^{\frac{1}{2}}, \qquad (37a)$$

where the specific heat for constant volume is separated into the translational and vibrational terms, c_{vt} and c_{vv}. At low frequencies, both terms are operative; beyond the frequency range $1/\tau$, as shown above, c_{vv} ceases to function, thus raising the value of the velocity.

The theory gives for the maximum absorption the equation

$$\lambda\alpha_{\max} = \frac{\pi}{2} \frac{Rc_{vv}}{c_{vt}(R + c_{vv})}, \qquad (38)$$

where the c_v components are known from thermal data. The agreement between theory and experiment is shown in Table III according to Kneser and Knudsen.[14] A comparison between specific heat data from supersonic dispersion and vibrational terms obtainable from spectroscopic measurements is given in a paper by Jatkar[15] for C_6H_6, CCl_4, and CS_2.

It can be seen from the above discussion that the theory of Kneser is well able to explain the remarkably high absorption of sound waves in gases that could not be accounted for on the basis of purely viscous phenomena.

TABLE III. *Maximum sound absorption coefficients from data of Kneser and Knudsen.*

Gas	Temperature, Deg. C	Measured Frequency Range in Kc	$\lambda\alpha_{\max} \times 10^3$	
			Measured	Calculated
Air	20	3–10	2.17–2.11	2.18
Air	55	3–10	4.10–3.59	3.94
Oxygen	20	3–6	10.6–10.3	10.4
Oxygen	55	3–6	20.1–18.9	18.8

Of particular practical importance is the role of humidity for the absorption coefficient of air. It has been known for some time that the absorption in air in the acoustical frequency range is considerably reduced with increasing humidity. The reason was unknown; only some vague notions existed as to the water molecules "lubricating" the gas molecules. Today this effect is better understood, even if not thoroughly explained. The main point is that the water molecules reduce the relaxation time of the air molecules and consequently shift the maximum toward higher frequencies. This can be seen from Fig. 14 indicating the influence of the percentage of H_2O (and NH_3) on the frequency of maximum absorption in oxygen. The absorption curves for different relative humidities in air as a function of frequency are shown in Fig. 15. The shift of the curves toward higher frequencies and the subsequent decrease of absorption in the acoustical range (say, below 5000 cycles) is clearly to be seen. In the supersonic

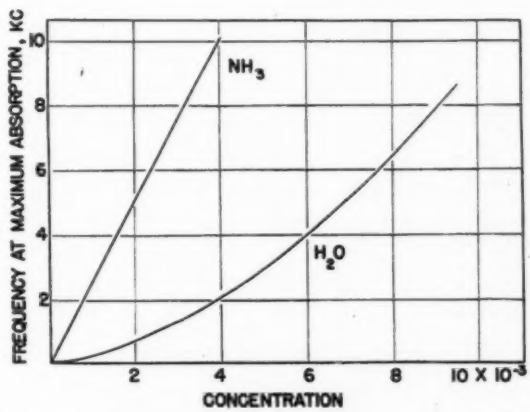

FIG. 14. Influence of admixtures of NH_3 and H_2O on the frequency of maximum absorption in oxygen, according to Kneser.

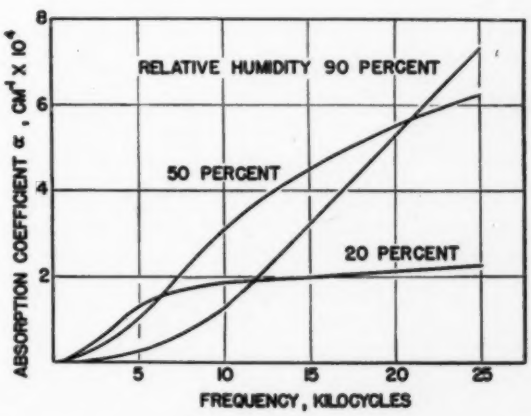

FIG. 15. Influence of relative humidity on the sound absorption of air at 20°C, according to Kneser.

range, on the other hand, the absorption increases with increasing humidity. The particular mechanism of the water molecules in reducing the average life of excited molecules need not be discussed here further.

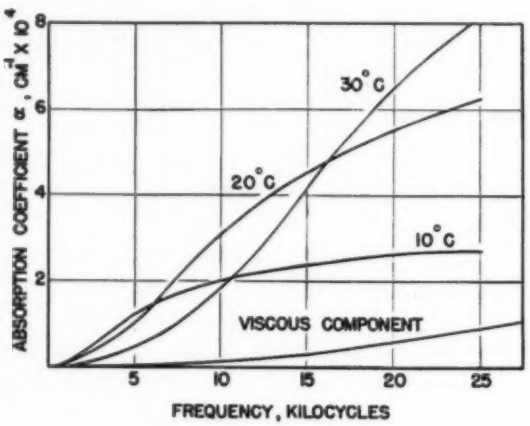

FIG. 16. Influence of temperature on the sound absorption of air, containing 50 percent humidity, according to Kneser.

Recent work by Pielemeier and co-workers[16] shows how absorption is changed with a given frequency and increasing humidity in carbon dioxide gas. It also explains most of the observed facts theoretically. Itterbeek[17] compares the effects of water and deuterium oxide in oxygen and carbon dioxide gases. The ratio of the relaxation times in D_2O and H_2O is about 1.5.

Figure 16 shows, also according to data of Kneser, the absorption in air containing 50 percent humidity for different temperatures. Higher temperature shortens the relaxation time, as is to be expected, and seems also to increase the maximum value. This is due to an increase of c_{vv}/c_{vt}, see Eq. (38), caused by the increasing possibilities of intramolecular vibrations with an increase of temperature. The figure also shows the portion of absorption due to purely viscous processes.

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Frictional Phenomena. IV

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Chapter IV. Sound Absorbing Materials

Abstract

IN this chapter a technical application of gaseous viscosity in the field of room acoustics is given. After a brief introduction into room acoustics, the absorbing property of sound-absorbing materials is explained on the basis of viscous processes in the pores of the material. Experimental data are in fair agreement with this explanation. It is even possible to derive the characteristics required for the most efficient absorbent, important from the standpoint of their manufacture.

15. Principles of Room Acoustics

Whereas in the preceding chapter a particular application of viscosity in gases to a field of essentially physical and physico-chemical interest was given, here we deal with a more practical application, namely, sound-absorbing materials. In order to make the matter understandable for those not too familiar with acoustics, a brief introduction into these aspects of sound absorption will follow.

In Section 12 a sound wave was described by means of the gas velocity u. It is just as common to work with the sound pressure p (see Eq. (30)); indeed, p is more frequently used than u where direct measurements are concerned, since most instruments respond to the pressure. In talking of p, the constant atmospheric pressure is generally disregarded, and p contains only the small alternating pressure superimposed upon the atmospheric pressure. In any medium there is a direct proportionality between p and u (taking their amplitudes, for instance), and we write

$$p=Zu, \tag{39}$$

where Z is called the radiation resistance. Generally, p and u are not in phase, and if we denote them—as is usually done—as complex quantities, then Z also will be complex. But in a plain wave p and u are in phase, as can be seen from curve 1 of Fig. 11, the volume being in phase quadrature with the displacement, and, therefore, in phase with the velocity. Thus, for plain waves, Z is a real quantity, and denoted by Z_0, the so-called characteristic resistance of the medium. As the theory shows,

$$Z_0=\rho c \tag{40}$$

(ρ=density, c=wave propagation velocity). Z_0, generally expressed in absolute c.g.s. units, so-called acoustic ohms, has a value for air of 41.5.

The pressure p is a measure of the amplitude of the sound, and p^2 is a measure of the intensity. The intensity level is measured in decibels. Each time the intensity is raised in a ratio 1 : 10, the decibel is increased by adding 10. Raising the pressure p in a ratio 1 : 10 increases the intensity 1 : 100, and the number of decibels by 20. From this we have the formula for the level L in decibels

$$L=L_0+20\log_{10} p. \tag{41}$$

The constant L_0 is fixed arbitrarily so that L should become zero at the threshold of audibility, i.e., at 2×10^{-4} dyne per sq. cm. With this condition, Eq. (41) becomes

$$L=74+20\log_{10} p \tag{42}$$

as can easily be verified. Loudness of any noise is measured by the decibel level of a tone of frequency 1000, giving the same loudness as the noise in question. As an illustration, the noise level in a typist's office is about 75, that in a quiet office 42, and that of a country residence 26.[1]

Noise abatement is one of the most acute problems today. There are three chief ways of reducing noise level. In order to fix our ideas, let us suppose there is a noisy machine in the workshop of a factory. Its noise reaches an office and must, therefore, be reduced.

First, it is possible to introduce certain alterations in the machine that will reduce the noise generated. This is the most logical method, but it is not always feasible.

Second, it is possible to insulate the office

effectively from the machine room. Partition walls transmit the sound from one room to the other; thus, a wall with a higher insulation is required. This method is useful, too, but has its limitations. It was found that the insulation of a wall increases essentially with its mass. Heavy walls are the best insulators. Evidently there is a limit to making full use of this property, and it is fortunate that there is a third method at our disposal to reduce noise.

This third method is the annihilation of the sound energy by transforming it into heat by means of absorption. In the previous chapter it was shown how viscosity (and intramolecular vibrations) causes the acoustical energy to be transformed into heat. The process was considered for freely traveling waves whose absorption coefficients, as can be seen from Table II, are very small, although these figures increase considerably in regions where molecular absorption takes place.

The absorption process, due to viscosity, may be enhanced to a great extent, if the wave does not travel freely, but is forced to proceed in narrow channels. Qualitatively, the reason for this is easy to understand. In narrow channels the gas adheres to the solid walls (Section 10), and consequently large transverse velocity gradients are set up with strong viscous forces and considerable dissipation. This idea will be developed later on a somewhat more quantitative basis.

Materials that accommodate a large number of narrow channels are called sound-absorbing materials, and it is their performance with which this chapter is concerned. Before discussing the physical processes underlying their functioning, the beneficial effects of such materials on the loudness of a sound will be shown in a more general way.

Referring to our previous example, let us assume that, after making certain improvements in the noisy machine and after installing a number of insulating walls, a given sound energy corresponding to a source of output P (energy per second) penetrates into the office in question.

When the machine is switched on and the source of output P starts to operate, it will build up a certain sound intensity in the room. The question is, how high will be the final sound pressure p, and thus (Eq. (42)), the loudness? Equilibrium evidently will be reached when the energy entering the room (P) is equal to that destroyed by absorption. Let us define the total absorption coefficient of the room by A_t. The total energy present is proportional to p^2, that absorbed per second to $A_t p^2$. Thus $P \sim A_t p^2$. Carrying out the calculation, we obtain

$$p = 41 \times 10^3 (P/A_t)^{\frac{1}{2}} \text{ dynes/cm}^2. \qquad (43)$$

Thus, the equation shows immediately that the larger the total absorption, the lower the intensity level and the loudness in decibels. In order to increase A_t, sound-absorbing materials will be used as lining for the walls and ceiling of the office.

The predominant role of the absorption A_t of a room is evident from its effect not only upon the pressure, but also upon the so-called reverberation time t_r which characterizes the acoustical quality of a room. It was mentioned in the previous paragraph that in switching on the machine in question, the pressure p will be built up. This has to be taken nearly literally; in fact, it takes a certain time until the process is practically finished according to an exponential time function. The theory shows that high absorption shortens the time of adjustment and vice versa; in the form of an equation:

$$t_r = V/600A_t \text{ sec.}, \qquad (44)$$

where V = volume of room in cc. If we think of V as the volume of a basin, P as the output of a water tap, A_t as the outlet at the bottom of the basin, and t_r as the time until the equilibrium height (p) of the water in the basin is reached, Eqs. (43) and (44) become immediately understandable. A sufficiently small reverberation time, of the order of 1 second, is necessary for the understandability of speech, and that shows the importance of a sufficiently large absorption.

While the absorption of rooms defines the reverberation time, and thus the acoustical quality of rooms, the reverberation time can be used to measure the absorption. There is apparatus available for automatic recordings of t_r, and such measurements are carried out for all the important concert halls and opera houses in the world. It was found that t_r is usually about 2 seconds for lower frequencies and 1 second for higher frequencies.[2]

Such rooms are, however, of rather complex structure, and not easy to analyze. In order to obtain simple conditions, A_t can be separated into several terms in the following way:

$$A_t = a_1 f_1 + a_2 f_2 + \cdots. \tag{45}$$

Here f_1, $f_2 \cdots$ are the surfaces (walls, ceiling, etc.) referring to different materials, each of which has a characteristic absorption coefficient a_1, $a_2 \cdots$. The absorption coefficient is here defined as the ratio of intensities of the absorbed and incident waves. This equation is utilized if a for an unknown absorbing material has to be determined. A special room with reflecting walls and having a large reverberation time is used for the purpose. In order to measure a for a given material, a given area of the floor is covered by it, t_r is recorded, and a is computed from Eqs. (44) and (45).

16. Theory of Sound-Absorbing Materials

Having thus explained the significance of sound-absorbing materials, the relation between the absorption coefficient and the viscosity constant of the medium (usually air) will now be discussed. For this purpose we must know the relation between a and Z, the radiation resistance of the material. The theory shows that a wave traveling in air is partly reflected if incident upon a wall of resistance Z, the ratio of the intensities of the reflected and incident waves being $(Z-Z_0)/(Z+Z_0)$. The reflection coefficient, which refers to energies instead of intensities, is the square of the above expression, and the absorption coefficient is evidently:

$$a = 1 - \left| \frac{Z-Z_0}{Z+Z_0} \right|^2. \tag{46}$$

Here we have used straight brackets, since the fraction is a complex quantity, and, before squaring, its absolute value (the geometric sum of the real and imaginary components) has to be taken. The problem is now reduced to the necessity of finding the relation between Z and the viscosity η of the air present in the channels of the absorbent.

In finding this relation, a further notation has to be introduced, namely Z_∞, this being the radiation resistance of the material of (practically) infinite thickness. This quantity Z_∞ can easily be deduced as a function of constants characteristic of the material. If Z_∞ is known, then Z_d, the resistance of a material of thickness d, is shown, theoretically, to be:

$$Z_d = Z_\infty \operatorname{cotanh}(ikd), \tag{47}$$

the meaning of k being explained later.

A rigorous deduction of the function $Z(\eta)$, valid for all frequencies, is mathematically rather involved,[3] so it should not be presented in this monograph. Instead, a simplified solution will be given that might be called the "low frequency solution." The theory shows that it is valid as long as

$$r^2\omega < \eta/\rho, \tag{48}$$

with $\omega = 2\pi\nu$, that is, either for low frequencies, or narrow channels. A satisfactory experimental verification of condition (48) is not available, but it appears that the "low frequency" solution agrees with experimental facts fairly well in the whole acoustical range and with the usual absorbing materials, even in cases where (48) has ceased to hold. For this reason only the simplified theory will be presented.

Qualitatively, the essential feature of the "low frequency" solution is that Poiseuille's Eq. (27), as deduced for the stationary flow in cylindrical tubes, holds. This implies first that the channels in an absorbent (Section 15) are idealized as having a cylindrical cross section; this, however, is not a serious restriction. The chief restriction lies in the assumption that Poiseuille's law, which was deduced for a stationary flow, will also hold for an alternating process. The assumption evidently will be valid if the wave-length of the wave is greater than the radial dimension of the tube (the usual condition for quasi-stationary processes); in other words, it will be valid for low frequencies and narrow channels, as stated above.

Exactly the same relations will be encountered in dealing with the oscillation-viscosimeter in the second part ("Liquids") of this monograph.

According to Eq. (27), the resistance coefficient R as introduced by Eq. (13) should now be calculated. However, R should now be defined as

$$R = p/u, \tag{13a}$$

taking the average velocity u, instead of V, the total flow (u times cross section). With the condition $\zeta=0$, (27) gives:

$$R=8\eta/r^2 \tag{49}$$

as the resistance or friction coefficient for the low frequency solution (r = radius of tubes).

This step having been taken, the introduced simplification can be easily visualized. A rigorous deduction ought to operate with the velocity at any given point, using the differential Eq. (8) for this case and integrating with respect to the radius. Here, on the other hand, the integration, as carried out for the stationary flow in (27) is taken as valid, and the differential equation will be written down afterwards for the average velocity. The equation has the form of (32) in which the first term is the inertia, the second the pressure gradient, and the third the viscous force. The latter takes, in our case, the form $-Ru$. Thus

$$\rho\partial u/\partial t+\partial p/\partial x-Ru=0. \tag{50}$$

It should be pointed out that ρ in Eq. (50) is, strictly speaking, not the density of the air, but the total vibrating mass in 1 cc. Since sound absorbents often contain a large number of light fibers, ρ is often larger than for air. To this equation another, to be derived from (30), (31), and (37) can be added:

$$\partial p/\partial t=-\kappa p_0\partial u/\partial x. \tag{51}$$

In Section 12, the solution was given in the form of a cosine function; here it should be given as a complex solution, which is sometimes more convenient. Thus

$$u=u_m e^{-ikx+i\omega t} \tag{52}$$

and

$$p=p_m e^{-ikx+i\omega t} \tag{52a}$$

with u_m and p_m as maximum values, and k the so-called phase or transmission constant of the absorbing medium. It is a complex number according to

$$k=\beta-i\alpha, \tag{53}$$

so that (52) becomes

$$u=u_m e^{-\alpha x}e^{i(\omega t-\beta x)}. \tag{52b}$$

It can be seen from this that α is the attenuation factor, and $\beta=\omega/c$, where c = propagation velocity (that of the air should be denoted by c_0). In substituting (52) into (50) and (51), one can see that the solution is correct if the components of k are given the following values:[4]

$$\beta=\omega(\rho/2\kappa p_0)^{\frac{1}{2}}\{[1+(R^2/\omega^2\rho^2)]^{\frac{1}{2}}+1\}^{\frac{1}{2}} \tag{54}$$

and

$$\alpha=\omega(\rho/2\kappa p_0)^{\frac{1}{2}}\{[1+(R^2/\omega^2\rho^2)]^{\frac{1}{2}}-1\}^{\frac{1}{2}}. \tag{54a}$$

Before discussing this result, the required function $Z_\infty(\eta)$ should be written down. Substituting (52) and (52a) into (51), the relation

$$\omega p_m=\kappa p_0 k u_m$$

is obtained. This means that only one of the amplitudes is arbitrary, the other being immediately determined by the above relation. Using the definition (39), we obtain for the radiation resistance $\kappa p_0 k/\omega$. This value refers to the pressure and velocity in the channels. Due to the limited porosity of the absorbent the expression must be changed in a way explained by Fig. 17.

Here a cross section unity is shown; on the left, air, and on the right, an absorbent. In our simplified picture, cylindrical channels are assumed, the ratio of the volume of which to the total volume is called porosity, P. In the figure a porosity of $\frac{1}{3}$ is shown diagrammatically. The arrow within a channel is the velocity u of Eq.

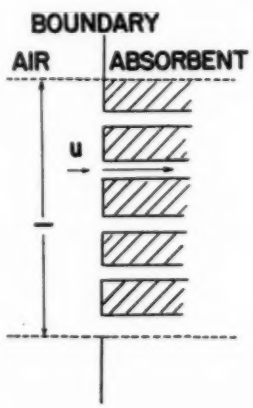

FIG. 17. Schematic diagram of boundary air-absorbing material.

(52). The quantity Z, however, always refers to a unit area. Thus we have first to transform u into the value that it would assume within the unit area just left of the boundary. Because of the continuity of flow, the velocities are in an inverse ratio to the effective areas; thus, the velocity left of the boundary is $u/3$, or, generally,

Pu. Taking this into account, we have

$$Z_\infty = \kappa p_0 k / P\omega. \tag{55}$$

Equation (55) together with Eqs. (54) and (49) is the answer to our problem, and allows the computation of the absorption coefficient a of a material, if its characteristic data, namely P, r, and η, are known.

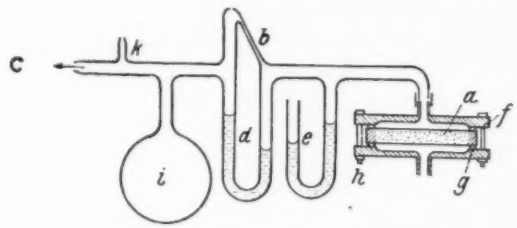

FIG. 18. Apparatus of Gemant to measure resistance R of absorbents by means of comparison with glass capillary.

17. *Measurement of Flow Resistance of Absorbents*

In order to review the experimental results on sound-absorbing materials, let us begin with a discussion of the characteristic data of absorbents.

(a) Little is known definitely about ρ, the mass of oscillating material in the unit volume. It appears that in materials built of stiff fibers ρ is very nearly equal to the density of air; in others containing loosely held light fibers which oscillate easily with the air, ρ is several times the density of air.

(b) The porosity P is generally high, around 0.7 or higher. It is desirable that it be high, since absorption of energy takes place chiefly within the air channels, as already mentioned. It can be determined by dipping the material into ethyl alcohol (water would cause swelling in certain cases) and finding the increase in volume per gram of material.

(c) The most important feature of the material is the resistance value R, Eq. (49). Expressing it in terms of η and r only was, of course, rather specific. More generally, relation (27) would yield

$$1/R = (r^2/8\eta)(1+4\zeta/r). \tag{49a}$$

The usual method for increasing R is a reduction of r, that is, a reduction of the fiber diameter (for a given packing), although an increase of the slip coefficient ζ also might bring about a change in the value of R.

In any case, since even Eq. (49a) is only approximate, it is essential to have methods of determining R experimentally, and in this connection two methods, developed by the author, should be mentioned.[5] Both determine R by means of a stationary air stream, in keeping with the "low frequency" assumption, discussed in the previous section.

One method compares the flow resistance with that of a glass capillary. If both units are connected in series, and the same air current passes through them, then the partial pressure differences are proportional to the resistances. The apparatus is shown in Fig. 18. Here a is the specimen, paraffinized at the edges, and b the glass capillary. From c, air is sucked into the apparatus. d and e are two water manometers showing the partial pressures; f stands for two heavy brass plates, g for rubber washers and h for bolts to keep the specimen airtight; i is an air container and k an outlet, both to buffer the fluctuations of the pump (usually a water pump).

The computation of R by means of this device is simple; R is given by:

$$R = (8l\eta PS/\pi r_c^4 d)\cdot(p/p_c), \tag{56}$$

where l = length, and r_c = radius of the capillary; S = surface; d = thickness of specimen, p and p_c = partial pressures across specimen and capillary; η, the viscosity of air, is 0.18×10^{-3} poise at room temperature.

Measurements are carried out at different pressures, and it is found that p_c/p increases with

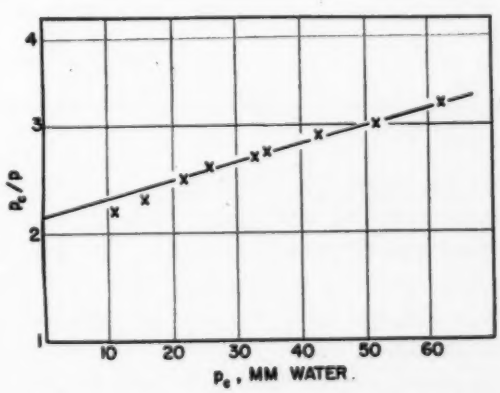

FIG. 19. Pressure data on Insulite (according to Gemant).

increasing pressure, because of turbulence in the glass capillary. The extrapolated value of p_c/p for $p_c=0$ is the correct one. Figure 19 shows the results on the material called "Insulite," the abscissae being p_c in mm of water. Using Eq. (56) and with $l=10$ cm, $r_c=6\times10^{-2}$ cm, $P=0.80$, $S=140$ sq. cm, and $d=1.3$ cm, $R=14\times10^3$ abs. units were obtained. A type of Celotex, another sound-absorbing material with porosity $P=0.70$, yielded $R=18\times10^3$. These materials are made of fairly thin fibers, but there are others, made of rather thick fibers, that have resistance values of the order of 10 abs.

The second method is a more direct one in that the velocity of the gas is measured by visual observation. This is achieved by adding carbon dioxide to the air, the presence of which can be detected by an indicator, like dibromo-thymol-sulfophthalein. This changes its color from blue to yellow if the pH drops below 6.8.

The apparatus used is shown in Fig. 20; a is a container for air under partial vacuum with manometer b and connection c to the pump. The vessel d contains a mixture of hydrochloric acid and sodium hydrocarbonate to develop CO_2; e is an air inlet. Several layers of the specimen, paraffinized at the edges and attached to funnels f, are in the path of the air stream. In the funnels

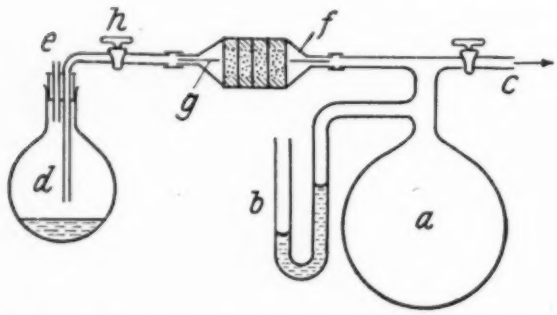

FIG. 20. Apparatus of Gemant to measure resistance R of absorbents by means of direct velocity readings.

there are little pieces of black board g with minute pieces of filter paper impregnated with the indicator solution; h is a valve, the opening of which starts the air current flow. The color change, left and right from the sample, indicates a certain time difference which is a direct measure of the velocity of the CO_2 molecules. By applying a correction due to the different molecular weights of air and CO_2 molecules, the velocity u of the air is obtained, and

$$R=p/du \tag{57}$$

(p=pressure difference, d=thickness of specimen).

Figure 21 shows the results for Insulite, the abscissae being pressure in mm of alcohol and the ordinates velocities of CO_2 molecules in cm/sec.

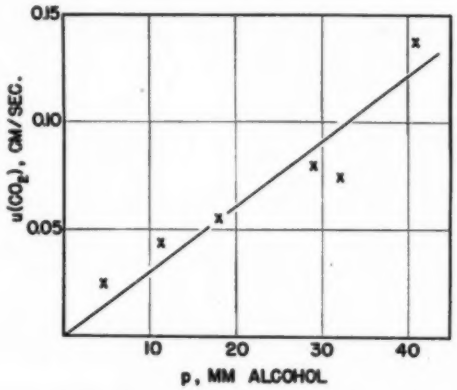

FIG. 21. Velocity data on Insulite (according to Gemant).

The line connecting the points should be a straight line through the origin. R, according to this method was 16×10^3, in fair agreement with the comparison method.

For materials of very low resistance the direct method is not suitable. Such a material of strong fibers and larger interstices called "Acoustic Plate" ($P=0.70$) gave, with the first method, $R=8.0$. Using for ρ the density of air (1.2×10^{-3}), the resistance components Z_1 and Z_2 according to $Z=Z_1+iZ_2$ were computed from Eq. (54), and are shown in the two curves of Fig. 22. The circles indicate actually measured values[4] by means of an electroacoustical method not to be discussed here. The agreement with regard to Z_1 (the term responsible for transmission) is very good; with regard to Z_2 (the term responsible for absorption), only fair. The ordinates are absolute units, called acoustic ohms.

18. *Experimental Facts on Sound Absorbents*

In discussing the behavior of sound-absorbing materials it is useful to consider first fairly thick layers for which Z_∞ gives the value of the radiation resistance, and afterwards thinner layers

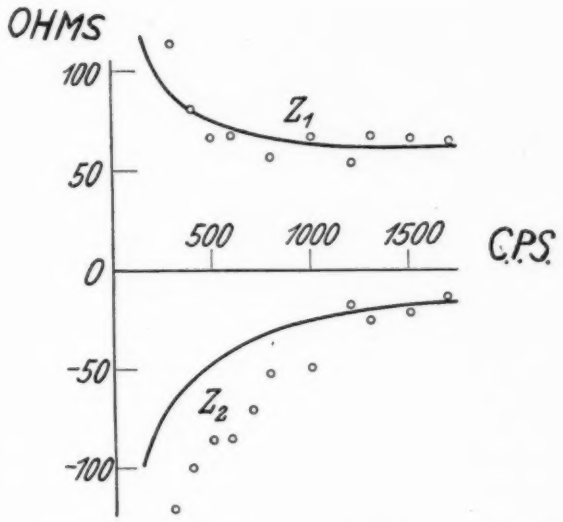

FIG. 22. Comparison of computed and measured values of radiation resistance for "Acoustic Plate" (according to Gemant).

(less than 1 inch) for which Eq. (47) has to be used.

(a) Thick layer of absorbent. It is interesting to follow the trend of absorption with varying frequency (by means of Eqs. (54) and (55)). For very low frequencies

$$\alpha=\beta=(R\omega/2\kappa p_0)^{\frac{1}{2}}, \tag{58}$$

which gives for the propagation velocity

$$c=c_0(r/2)(\rho\omega/\eta)^{\frac{1}{2}}$$

(c_0 = propagation velocity in air), indicating that the velocity is smaller than for air. The attenuation factor is proportional to the square root of the viscosity constant.

For high frequencies, on the other hand, α, and thus Z_2 tends toward zero, and Z_1 becomes

$$Z_1=(\kappa p_0\rho)^{\frac{1}{2}}/P. \tag{59}$$

As to the absorption coefficient a, which is of primary interest in this connection, the components of Z being very large for low frequencies (Eq. (55)), a becomes zero (Eq. (46)). Because of the high radiation resistance offered by the material, practically the whole wave is reflected; thus no absorption occurs. For high frequencies, although α is small, the radiation resistance is very nearly the same as for air; hence the largest part of the wave is, so to speak, lured into the channels, where (for large thicknesses) it will be destroyed: a is very near unity. These relations for Z_1, Z_2 and a for thick absorbents are shown diagrammatically in Fig. 23. An experimental curve according to Kühl and Meyer[4] is shown in Fig. 24, obtained from a layer of cotton wool 24 inches thick which follows the trend just deduced theoretically. This shows that the low frequency solution is quite useful in spite of its limitations. Figure 22, with its experimental and calculated values on the highly porous material (also 24 inches thick), reveals the same trend of the resistance components as a function of frequency.

(b) Thin layer of absorbent. Of more practical importance are layers (1 inch or less in thickness), for which Eq. (47) must be consulted in order to predict their absorbent properties. A brief presentation of an analysis of this case carried out by the author[6] will now be given, mainly because the analysis leads to a conclusion important from the standpoint of manufacturing sound-absorbing materials.

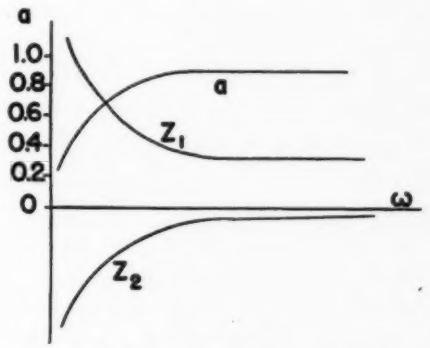

FIG. 23. Diagram of radiation resistance and absorption coefficient as function of frequency (thick specimens); ordinate-scale only for a.

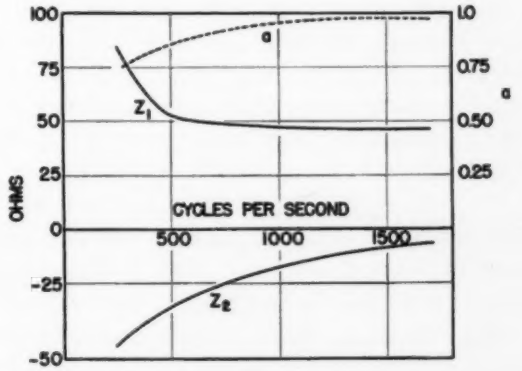

FIG. 24. Radiation resistance and absorption coefficient for cotton wool 24 inches thick (according to Kühl and Meyer).

A complete analysis of Eq. (47) is rather involved, and here, again, the extreme cases of high and low frequencies only will be considered.

Equation (54) shows that a critical frequency ω_c can be defined, according to

$$\omega_c = R/\rho, \tag{60}$$

so that the equations will be considerably

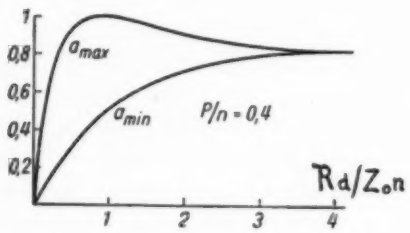

FIG. 25. Computed absorption coefficient as function of resistance coefficient for "high frequency" range (according to Gemant).

simplified if the frequency is either lower or higher than ω_c.

If $\omega > \omega_c$ (*high frequencies*), we know from the foregoing subsection (a) that Z_∞ assumes the value (59), whereas α is very small. Putting Z_∞ into (47), the following can be seen. Both components of Z_d, namely Z_1 and Z_2, are now periodical functions of the argument (βd). The reason for this is a resonance process: each time the thickness d is a multiple of a quarter-wavelength, standing waves will develop. In consequence of this, Z_2 goes through zero each time such resonance occurs, and Z_d becomes real, passing through maxima and minima. The absorption coefficient a is also a periodic function going through extreme values simultaneously with Z_d.

As the theory shows, the extreme values of a depend upon the argument $Rd/Z_0 n$, where $n = (\rho/\rho_{air})^{\frac{1}{2}}$, a figure equal to or larger than 1. Figure 25 shows a_{max} and a_{min} as functions of the argument $Rd/Z_0 n$ for the parameter $P/n = 0.4$. It should be recalled that a here is the limiting value reached for higher frequencies. It oscillates with varying frequency between the two extremes shown in the figure. It can be seen that unless the argument is larger than, say, 3, a will assume very low values at certain frequencies, which is undesirable. For good performance, the condition

$$Rd/Z_0 n > 3$$

must be satisfied. With an average value of $d = 1''$ and $n \sim 3$, this condition is equivalent to

$$R > 160 \text{ ohms}.$$

If, on the other hand, $\omega < \omega_c$ (*low frequencies*), we know from subsection (a) that α and β are equal, their value being given by expression (58). Substituting these values into Eq. (47) we see that a in this frequency range is not a periodic, but a monotonous function of the frequency. It is then possible to compute the radiation resistance components and the absorption coefficient by means of a graphical method. The result is shown in Fig. 26, presenting a as a function of the frequency, with R as parameter, taking $P = 0.8$ and $d = \frac{4}{5}''$. Here it is noteworthy that both low and high values of R are unfavorable, and that an optimum value of R exists. For $R < 200$ the absorption for lowest frequencies becomes too low, whereas for $R > 400$ the whole curve falls off. Thus in this low frequency range there is an optimum value for R, namely a few hundred ohms. For lower values the viscous forces evidently are too low, for higher ones the resistance becomes too high and the total wave is reflected: thus no full use is made of the viscous forces.

This result is in agreement with that for high frequencies, requiring a value of R above 160.

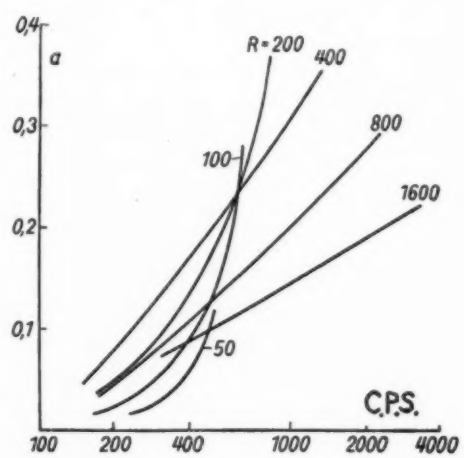

FIG. 26. Computed absorption coefficient for different resistance coefficients: "low frequency" range (according to Gemant).

From a manufacturing standpoint the chief conclusion to be drawn is that a certain medium value of fiber thickness (1 to 10 mils) will yield the best absorbent. The tightness of packing is determined by the condition that high porosity (around 0.7) be achieved. The chief remaining variable is, then, the fiber thickness, the channel diameter evidently increasing with the fiber diameter. According to (49) a certain medium value of diameter is required, and this should be around the above stated values.

19. Practical Applications

Finally a brief review of research, concerned with practical application of sound absorbents, should be given.

There exists a large number of materials, such as those already considered above, the absorption coefficients of which are known and which are used in the construction of rooms with certain desired acoustic properties. The computation of the final effect is, however, not always quite as simple as Eq. (45) would suggest, because of certain simplifying assumptions underlying that equation. Chrisler[7] found that for large areas present the total absorption is smaller than expected, and for small areas, on the other hand, it is larger than calculated. Pellam[8] investigated the effect of strips of absorbing panels placed upon rigid walls, and determined the shape factor giving the relative increase of absorption, as compared with the computed value from the known absorption coefficient. The factor is largest if the panel width is about half the wavelength of the sound.

A theoretical investigation of propagation of sound waves in closed spaces lined with absorbing materials is given by Bolt,[9] particularly with reference to the shape of the room, and also by Brillouin.[10] A résumé of the current knowledge on room acoustics was presented in several papers during the Tenth Meeting of the Acoustical Society of America.[11]

In computing reverberation times of large rooms, the effect of the audience (in concert halls, for instance) has to be considered, also that of cushioned seats. In case of the audience it is chiefly their clothes that absorb. It is customary to express the absorption in terms of equivalent open window surface (having a coefficient $a=1$). Figure 27 shows[2] the equivalent surface in square meters of each seat (1) and each person (2) as a function of frequency. A recent publication on this subject was written by Gigli.[12]

There are composite materials in use that contain larger air spaces within the fibrous structure. Such a material is, for instance, Vibraframe, the properties of which were measured by Ham and Darracott.[13]

A further point of interest is whether sound-absorbing panels can be painted for purposes of preservation or decoration, without an adverse influence upon their qualities. This question was recently investigated by Chrisler[14] who found that a few layers of paint are harmless, but that

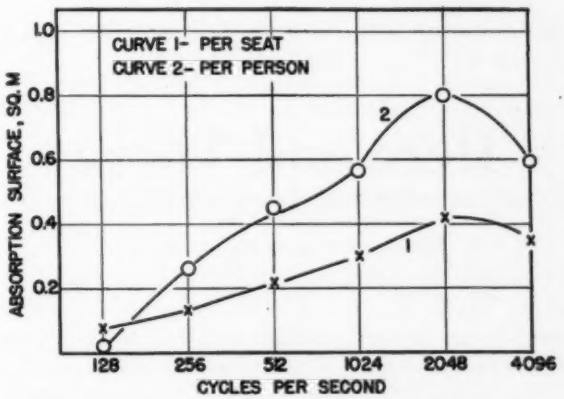

FIG. 27. Absorption values for cushioned seats and audience (according to Meyer and Jordan).

there is a very definite limit. As soon as the openings of the channels are blocked, the absorbing properties will evidently suffer.

Kaye and Evans[15] recently measured the absorption of some materials occurring out-of-doors. The absorption rises with frequency as shown in the theory (Fig. 23). Loose gravel and snow are highly absorbent; compressed gravel and wet sand are only slightly so. The reason is probably in their widely differing porosity.

Fiber glass which has only recently been produced on a large scale for both mechanical and electrical purposes, is used also as a sound-absorbing material.[16] It seems to the present writer that fiber glass is rather suitable for this purpose, since the thickness of the fibers can be varied through a wide range to yield the optimum structure specified above.

Sound-absorbing materials are used in ventilator and exhaust systems, the ducts of which are lined with suitable materials like rock-wool, in order to obtain an attenuation of sound waves passing the ducts. Theory and experiment on such ducts are presented by Sivian[17] for the low frequency range, and by Rogers,[18] covering both high and low frequencies, also by Morse[19] for both rectangular and circular cross sections of the ducts.

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Here and There

Meetings of Scientific Societies

The sixty-seventh annual general meeting of the Physical Society was held on July 25. The following officers for 1941–42 were elected: *President*, Dr. C. G. Darwin; *Hon. Treasurer*, Dr. C. C. Paterson; *Hon. Secretary* (*Business*), Dr. W. Jevons; *Hon. Secretary* (*Papers*), Mr. J. H. Awbery; *Hon. Librarian*, Dr. L. C. Martin; *New Members of the Council*, Professor E. N. da C. Andrade and Dr. H. Shaw. At this meeting the first Charles Chree Medal and Prize were presented to Professor Sydney Chapman, who delivered an address on Chree's work on geomagnetism, part of which appears in *Nature* **148**, 153–160 (Aug. 9, 1941). Professor Chapman's distinguished work for the advancement of the science of geomagnetism began in 1911, when he was appointed to the Royal Observatory at Greenwich to design new instruments and buildings for magnetic observations.

★

The twenty-sixth annual meeting of the Optical Society of America will be held in New York City on October 24 and 25 with headquarters at the Hotel Pennsylvania. A symposium on the role of "Optics in the National Defense" is scheduled for the session on Friday morning, October 24. The annual dinner is to be held on Friday evening, when the Frederic Ives Medal will be awarded. The Acoustical Society of America and the Society of Rheology will hold their meetings simultaneously with the Optical Society, and the Society of Motion Picture Engineers will hold its meeting at the same hotel from October 21 to 23.

The Electrochemical Society will hold what is expected to be its largest convention at Chicago, October 1 to 4, 1941. An extensive industrial exhibit will be an integral part of the meeting. Exhibition material has also been contributed by a number of universities in the Chicago area. Special plans have been made to take care of the large number of senior and graduate students expected to attend. Introductions will be made for students, and an employment committee will function for their benefit. Dr. Zworykin, head of the RCA Electronic Research Laboratory, will address the convention on "The Electron Microscope." Several sessions will be devoted to electrodeposition and to electroorganic chemistry.

★

National Research Council Conference on Electrical Insulation

The historic city of Williamsburg, Virginia, has been chosen for the 14th annual meeting of the Conference on Electrical Insulation of the National Research Council, Division of Engineering and Industrial Research. The meeting will last three days, beginning on October 30. As usual there will be many reports on investigations covering different problems in the field of dielectrics. In addition it has been planned to devote one session to a discussion of problems arising from actual or potential shortages of certain insulating materials. A program for the meeting may be obtained by writing the Secretary of the Conference, Thorstein Larsen, Consolidated Edison Company of New York, Inc., 55 Johnson Street, Brooklyn, New York.

Research Director Receives Honorary Degree

An honorary degree of Doctor of Science in engineering was conferred recently upon Dr. Harvey C. Rentschler, Director of Research since 1917 for the Westinghouse Lamp Division, Bloomfield, New Jersey, by Princeton University. Dr. Rentschler was cited for his talents in the investigation of photoelectric cells and x-ray and electron tubes. He has pioneered in the development of such devices as the germ-killing Sterilamp, fluorescent lamps, new radio tubes and high intensity mercury vapor lamps. Rare metals, such as thorium, tantalum, and titanium, long suspected of being suitable for use in photoelectric cells, were first applied as coatings for practical cells through Dr. Rentschler's experiments.

★

University of North Carolina

The following news items come from the University of North Carolina: Dr. Russell Lyddane has gone to the U. S. Naval Proving Grounds. He is being replaced temporarily by Dr. E. P. Cooper from the University of California. Professor Earle Plyler has a leave of absence for a year to do important industrial work at Ann Arbor. Dr. Nathan Rosen, formerly Einstein's assistant, has been added to the permanent staff of the University.

★

Precautions During Storms

Dr. P. L. Ballaschi, Westinghouse engineer, has drawn the following conclusions from a survey of more than 100 lightning fatalities. First and most important, get under a shelter as quickly as possible. Houses, barns and other buildings—the bigger the better—are good shelters. The top and sides of buildings will usually provide a better conductor path than the human body for lightning to reach the ground. When a storm threatens, keep off golf courses, suspend outdoor games, don't ride bicycles or horses and don't operate exposed machines such as tractors. Avoid shelter under trees, particularly isolated trees. Stay away from poles, masts, and other exposed objects projecting skyward. Stay in your car if an electrical storm suddenly develops while you are motoring. About 90 percent of lightning casualties occur in rural districts and open spaces where the exposure hazard is greatest. Barns, farm houses and structures located on the outskirts of cities are made safer by the erection of lightning rods.

★

Largest Power Source

The first of three 108,000-kw Westinghouse generators, each driven by a 150,000-horsepower waterwheel, is now working at the Grand Coulee Dam. Energy from the Grand Coulee West Power House will be transmitted over a 230-kv line to Bonneville Dam, on the lower Columbia, where it will be made available for use in the new aluminum-manufacturing plant at nearby Vancouver, Washington. The second machine is expected to go into operation about December 1 and the third is scheduled for completion in March, 1942. When completed the generating plant at Grand Coulee Dam will be the largest single source of power in the world and will comprise 18 main generators, all of the 108,000-kw size, and three 10-kw "station service" generators which will provide power for the power house itself. Power from the big machines will fill many defense requirements and peacetime industrial needs in an area about twice the size of New England.

★

Magnesium Manufacture

New American plants are making magnesium from sea water in such quantities that the United States and England are now equaling and will surpass Germany in production of this strategic material. Up to three years ago Germany produced three-fourths of the world's consumption. Dr. R. H. Harrington, metallurgist in the General Electric Research Laboratory, declared in a G.E. Science Forum address at Schenectady that early in 1939 it became apparent that our metal supply would be inadequate, and new production facilities were provided which increased production by nearly 100 percent to 12 million pounds for 1940. A yield of 30 million pounds is expected for 1941. This expansion is being made possible by new plants which use sea water as a source. There are about four and one-half million tons of magnesium in a cubic mile of sea water, according to Dr. Harrington.

★

Recent Factory Expansions

Because of the tremendous increase in its business volume, the Wheelco Instruments Company has moved to its own building, located at Harrison and Peoria Streets, Chicago, Illinois. This is the third major expansion of the company since its establishment in 1935.

A factory addition, doubling the production space, has been announced by the Ohmite Manufacturing Company, West Flournoy Street, Chicago, Illinois.

New Books

Polarography

By I. M. Kolthoff and J. J. Lingane. Pp. 510+xvi, Figs. 141, 16×23½ cm. Interscience Publishers, Inc., New York, 1941. Price $6.00.

The authors state that they have written this monograph on polarography because there is pressing need for such a book in the English language, and their comprehensive and critical treatment of the subject up to its present status of development makes the book indispensable to anyone interested in this steadily growing field.

After a short general introduction, the first half of the book is devoted to a much needed theoretical discussion of the principles governing polarography. MacGillavary's derivation of the equation for the diffusion current, which is the basis of quantitative polarography, is included, although Ilkovic's original derivation is much simpler and more instructive and gives the same result. In separate sections, treatments of the migration current and condenser current are given, and these are followed by a discussion of maxima in polarographic waves. The inclusion of sections on diffusion of ions and the electrocapillarity curve of mercury which is intimately related to polarography will certainly bring about a better understanding of this complex subject, required for successful practical polarographic work.

A consideration of the many other different factors influencing the half-wave potential which is significant in qualitative polarography follows, and it should be said that the dropping amalgam electrode on which Heyrovsky has written an extensive treatment deserves more than the one sentence devoted to it. The discussion of complex ion waves contains many observations by one of the authors which have not yet been published, and this makes the chapter quite valuable. The interpretation of the waves of organic substances gives a clear picture of the factors which must be considered in order to get reproducible results and which have not been fully recognized in the past. The theoretical part is closed by a chapter on catalytic hydrogen waves and mixed potentials introduced into polarography by J. M. Kolthoff.

The treatment of the apparatus and technique is understandably short because different types of commercial apparatus are always accompanied by detailed instructions. No mention is made of the rather important bridge circuit for continuous cathodic and anodic polarization or the Uhl method of adding known amounts of a standard polarographically inactive reagent for use in calibration. Instead of simply referring to the original literature for obtaining the cell resistance, practical description of this and the application of the *IR* correction for half-wave potentials which is not always applied would have been valuable. In the part on inorganic analysis, the elements are treated in groups, and much information is critically summarized with great care. This part is closed by a chapter on technical analysis.

Organic compounds are treated according to their functional groups rather than only as individual substances, and although it is still somewhat early to expect a complete treatment along these lines, one can now realize how such a treatment will look after more precise information is available. The biological application involves chiefly proteins and sulphydryl compounds, and the detailed description of Brdicka's cancer test will help to decide its true value by inspiring new experiments.

After a description of the work done with the platinum microelectrode, the book closes with an introduction to amperometric (polarometric) titration. Many statements here (especially in the theoretical part) are only approximately true, but this is to be expected in such a new field. The value of the appendix, which may be obtained separately from the book would be increased if references had also been included there.

The book should stimulate further research, not only in the field of analysis, but also in chemical physics, since information can be obtained about diffusion coefficients, oxidation reduction potentials, dissociation constants of ions correlated close to the field of electrolysis on electrodes where polarization occurs.

The paper and typography of the book are excellent.

The book is dedicated to Professor Heyrosky, who not only invented polarography but, with his co-workers at the Charles University at Prague, was mostly responsible for developing it to its present state.

ALOIS LANGER
Westinghouse Research Laboratories

Atlas of Charts on Physical Chemistry

By G. V. VIŇOGRADOV AND A. I. KRASILSHIKOV. 195 charts, 12×17 inches, and 150 pages of descriptive material. State Publishers of Technical-Theoretical Literature. Moscow-Leningrad, 1940.

This voluminous work consists primarily of 195 charts for calculating quantities important in the study and applications of physical chemistry. The text is not lengthy, but devotes itself mostly to indices and guides to aid in using the charts; it does contain some descriptive material, however, on the use and construction of charts in general.

The charts themselves represent a very large compilation of data. They will prove useful wherever quick or numerous calculations involving the more complicated formulae of physical chemistry must be made. Some attention has been paid to formulae of chemical thermodynamics, but more particularly to chemical processes described from the molecular-kinetic point of view.

The scope of this atlas can perhaps best be appreciated by considering the sections into which it is divided. The headings of these divisions are: (1) Gases; (2) Adiabatic and polytropic processes; (3) Kinetic theory of gases; (4) Thermal capacity, free internal energy, and entropy of solid bodies; (5) Vaporization and boiling; (6) Surface tension and adsorption; (7) Polarity characteristics of gases and dissolved substances; (8) Solutions; (9) Electrochemistry; (10) Several properties of dispersion systems of hydrosols and aerosols; (11) Several formulae on chemical kinetics and thermodynamics; (12) Several formulae on measurement technique.

JOHN E. WHITE
University of Pittsburgh

New Instrument Booklets

The current issue of the Tin Research Institute's *Quarterly Review* describes several important new developments. In seeking for a substitute for aluminum for milk bottle caps, a new alloy of tin, zinc, and nickel was discovered which has a remarkable combination of strength and ductility. The improved tin foil rolled from this alloy has 2½ times the strength of ordinary tin foil. Other items, such as the discovery of a new tin-rich bearing alloy, suitable for use in the tail-shaft bearings of large ocean-going vessels, and properties of non-corrosive solder fluxes obtained by neutralizing certain organic acids with amines, are included in the current issue of *Tin and Its Uses*, No. 10, which may be obtained from the Tin Research Institute, Fraser Road, Greenford, Middlesex, England, or from the Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio.

Two booklets from the Tin Research Institute, Fraser Road, Greenford, Middlesex, England, entitled "Protective Films on Tinplate by Chemical Treatment" (Publication No. 104), and "Report for 1940" (Publication No. 103).

A New Wheelco Thermocouple Data Book and Catalogue has just been issued by the Wheelco Instruments Company, Harrison and Peoria Streets, Chicago, Illinois. This catalogue contains temperature conversion tables, millivolt tables, pipe and wire sizes, decimal equivalents, wire resistances, recommendations for checking thermocouples and pyrometers, and information on how to construct thermocouples, as well as prices and descriptions of the various items offered for sale.

"The Electrophoresis Apparatus with Improved Optical System," illustrated descriptive material about a product of Adam Hilger, Ltd., 98 St. Pancras Way, Camden Road, London, N.W. 1, England.

"Oxygen-Boosting of Diesel Engines for Take-Off," Bulletin No. 54 of the Engineering Experiment Station Series, The Pennsylvania State College, State College, Pennsylvania. Copies sell for 50 cents each.

The General Radio Company's *General Radio Experimenter*, June, 1941. Feature article, "The Vibration Meter —A New Electronic Tool for Industry." The General Radio Company is located at 30 State Street, Cambridge, Massachusetts.

Illustrations, current prices, and descriptive material concerning "RCA radio and television test equipment" make up Catalog No. 105, distributed by Cameradio Company, 963 Liberty Avenue, Pittsburgh, Pennsylvania, and 1002 Main Street, Wheeling, West Virginia. This 27-page catalog contains information on signal-tracing equipment, electronic voltmeter-ohmmeter, tube testers, oscillographs, signal generators and test oscillators, service equipment, antennas, record players and accessories, television parts, replacement parts, transmitting tube sockets, communication receiver, and transmitting tubes.

Application in the bottle washing field of the Solu-Bridge, electrical instrument for direct measurement of concentration of washing solutions, is described in a leaflet distributed recently by Industrial Instruments, Inc., whose new plant and offices are located at 156 Culver Avenue, Jersey City, New Jersey.

"Frahm" vibrating-reed tachometers form the theme of Bulletin 1670, published by the James G. Biddle Company, 1211–13 Arch Street, Philadelphia, Pennsylvania. The product is described briefly as follows: "The sole mechanism in a Frahm Tachometer is a set of accurately calibrated or 'tuned' steel reeds. The slight vibration caused by the rotation of the machine on which the instrument is mounted produces a sympathetic or resonant vibration in certain of these reeds. This in turn is instantly readable on the scale as revolutions per minute."

Data pertaining in general to the Shallcross rotary instrument switches and in particular to the four standard types manufactured by the Company, have been collected in Bulletin No. 500 issued recently by the Shallcross Manufacturing Company, Collingdale, Pennsylvania.

Polaroid Laboratory Products is the title of a recent booklet issued by the Chicago Apparatus Company, 1735 Ashland Avenue, Chicago, Illinois. The Polaroid products described and illustrated in this catalog are offered to implement the new and expanding interest in the new field of applied science created by Polaroid light-polarizing materials. These products provide means for demonstration, instruction and research.

The photo-tube's usefulness in light-operated relays, color discriminating devices, automatic counters, light measuring, and film sound reproduction is explained in detail in a 16-page booklet prepared by the RCA Manufacturing Company, Camden, New Jersey. The booklet is being distributed to engineers, servicemen, amateurs, students, and experimenters throughout the country by RCA transmitting tube distributors. Numerous circuits, characteristic curves, and charted data on the RCA photo-tube line, supplement the descriptive material.

The Gray Instrument Company, 64 West Johnson Street, Germantown, Philadelphia, Pennsylvania, has distributed recently its Catalog E-14, *"Queen" Instruments*, describing and illustrating the Company's line of potentiometers, Wheatstone bridges, Kelvin bridges, galvanometers, Kohlrausch slides, resistance boxes, resistance standards, volt boxes, and other electrical measuring equipment.

Contributed Original Research

A Preliminary Report on the Development of a 300-Kilovolt Magnetic Electron Microscope

V. K. Zworykin, J. Hillier, and A. W. Vance
Research Laboratories, RCA Manufacturing Company, Camden, New Jersey

(Received August 1, 1941)

Electron microscopes using accelerating potentials of from 30 to 100 kilovolts cannot be employed satisfactorily for the examination of specimens whose thickness is greater than one-half micron (in the case of organic material). In order to investigate the possibility of applying the high resolving power of the electron microscope to problems involving somewhat thicker specimens, an instrument has been constructed which uses electrons accelerated by voltages up to 300 kilovolts. A commercial electron microscope has been adapted for the purpose by the modification of the electron gun and projection lens, and by the addition of a new high voltage generator. The essential features of the new design and some of the problems encountered in the testing of the equipment are described. Comparison micrographs of test objects taken with 50- to 250-kilovolt electrons demonstrate the increase in penetrating power obtained at the higher potentials. An electron micrograph of a biological section, one to two microns thick, taken with 200-kilovolt electrons shows a promising amount of the internal structure.

THE primary purpose of the research work carried out in the development of the electron microscope has been the attainment of maximum resolving power accompanied by the simplification and improvement of the operation of the instrument.[1,2] The developmental work has resulted in the construction of a considerable number of electron microscopes and in a design which has recently been made available on a commercial basis. The best resolving power that has been demonstrated with an electron microscope of any kind lies in the range between 30 and 50A, while that obtainable under ordinary working conditions appears to be of the order of 100A.

If it were possible to obtain the resolution of details of the above magnitude *for all* microscope specimens, the research worker would have at his disposal a device for observing directly all those phenomena of nature which take place in the range of the size scale above 50 angstrom units. Unfortunately, in the images obtained with the present types of instrument using electrons accelerated by from 30 to 100 kilovolts, those parts of the specimen which are thicker than about 5000 angstrom units in the case of organic materials, and thicker than a few hundred angstrom units in the case of heavy metals, appear nearly opaque and completely lacking in detail. As many important problems of biology involve the investigation of fine structure which is an integral part of a relatively large body, and which cannot be removed from that body without loss of identity, this lack of penetration is probably the most important limiting factor in the present types of electron microscopes.

In order to investigate the possibility of obtaining images of the internal structure of thicker specimens by the use of higher voltages for the acceleration of the irradiating electrons, the authors have constructed in the RCA Laboratories an experimental magnetic electron microscope capable of producing images of high resolving power with 300-kilovolt electrons. Except for the design of the high voltage generator and a few modifications of the microscope column resulting from the change to higher accelerating potentials, the instrument is the same as that which has already been described.[1] Figure 1 is a photograph of the equipment with the electro-

[1] J. Hillier and A. W. Vance, "Recent developments in the RCA electron microscope," Proc. I. R. E. **29**, 167–176 (April, 1941) (and references contained therein).
[2] B. von Borries and E. Ruska, Siemenz Zeits. **20**, 217 (1940).

static and lead shielding removed. The standard microscope column and cabinet can be seen at the right while the tank containing the high voltage generator is visible at the left.

The high voltage generator and regulator operate on the same principles as those which have been described in connection with the lower voltage generator.[1] The oil-immersed rectifier-filter system is a voltage quadrupler of the Cockcroft Walton type but designed to operate at radiofrequency. As in the commercial unit the rectifier-filter system presents a series-resonant radiofrequency load to a driver-oscillator circuit. In the latter circuit it was found necessary to use a 1-kilowatt air-cooled tube in order to obtain sufficient power for the high voltage requirements. Separate radiofrequency oscillators supply the heating current for the rectifier and microscope filaments through step-down insulation transformers mounted in the oil tank. The design of the feed-back regulator used to stabilize the high voltage is similar to that which has been described in the previous papers.[1,3] The output voltage may be varied from 50 to 300 kilovolts in 50-kilovolt steps by a control on the panel.

The quadrupler-rectifier system filter and voltage divider are mounted in the large oil tank. The problem involved in obtaining a suitable insulator for the high voltage outlet from the tank was solved by using a specially molded disk of hard rubber, surrounded by a boiler plate flange six inches wide, to form a cover for the entire open top of the oil tank. All of the electrical equipment which is contained in the oil tank is mounted on a framework and supported as a single unit on the under side of the cover in such a way that it can be removed from the tank with the cover. The high voltage terminal is in the form of a large copper sphere, mounted on a cylindrical rod which is tightly sealed in the center of the hard rubber disk. Stresses in the hard rubber disk are reduced by three tubular copper rings of a large diameter tubing mounted concentrically with the high voltage terminal. The first of these rings is mounted on the upper side of the hard rubber disk, midway between the center and the rim. The second which has the same outside diameter as the first but which is constructed of somewhat smaller diameter tubing, is mounted on the under side of the hard rubber disk. The first and second rings are mounted and electrically connected by means of screws passing through and sealed into the rubber. This system of rings is maintained at half the full voltage by means of a high resistance voltage divider. The third ring is mounted on the upper side of the hard rubber on its circumference,

[3] A. W. Vance, "Stable power supplies for electron microscopes," RCA Rev. **5**, 293–300 (Jan. 1941).

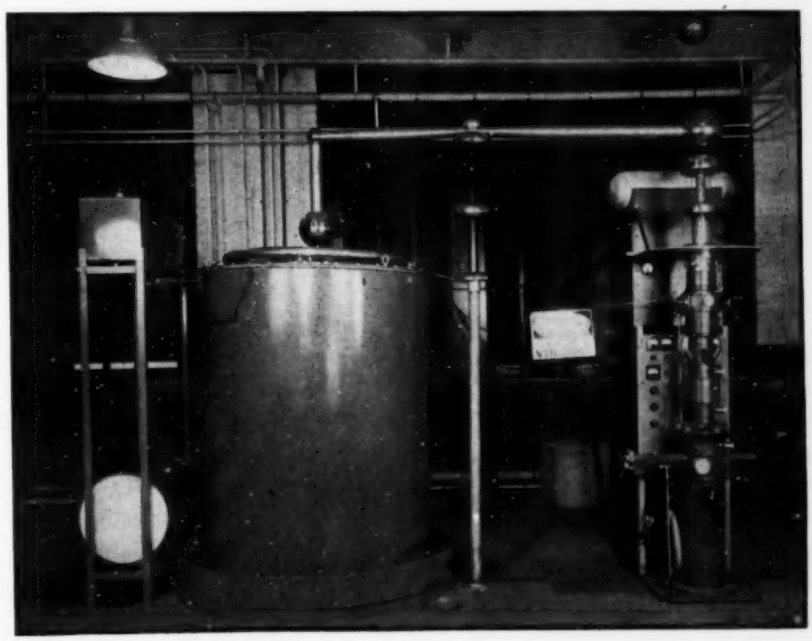
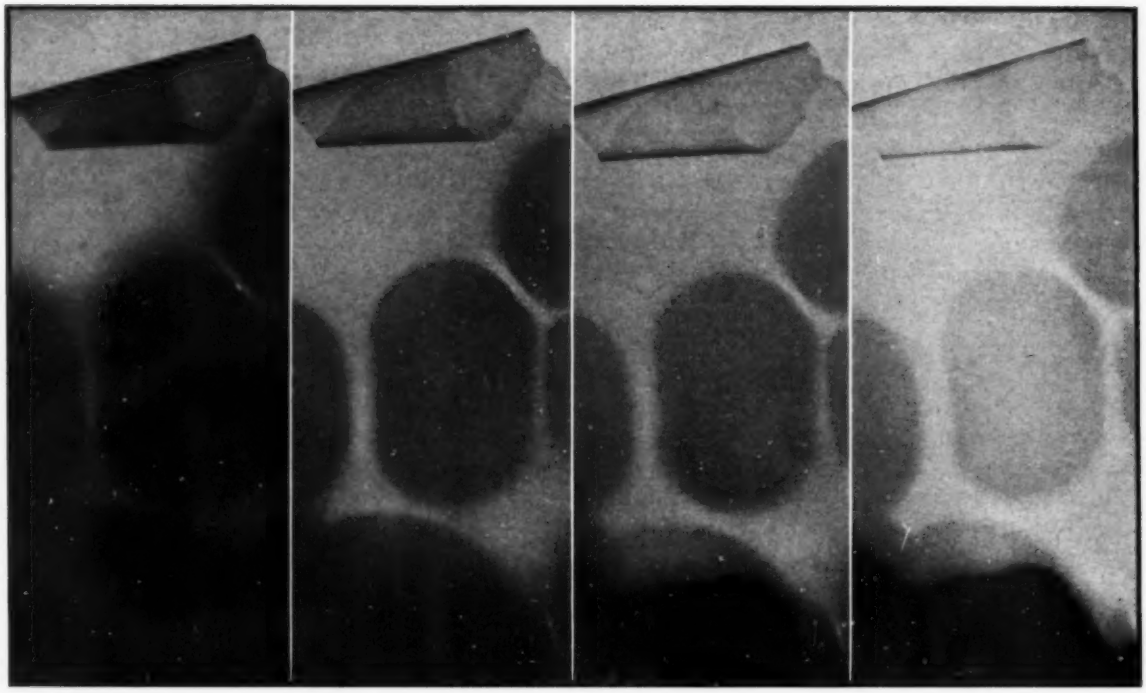


FIG. 1. Photograph of new 300-kilovolt electron microscope.



50 kv 100 kv 150 kv 200 kv

FIG. 2. Magnification 5000.

and is connected to the grounded tank. In order to prevent air bubbles from being trapped under the hard rubber disk, the tank has been mounted on a slightly inclined platform. A stopcock is mounted on the highest point of the tank and is used to release the last traces of air when the tank is filled. A reservoir, which is supported above the level of the top of the large tank can be seen at the extreme left in Fig. 1. This reservoir is connected to the top of the large tank and is maintained about half full of oil. It serves to take care of the thermal expansion of the oil in the large tank during operation, and to take care of any loss of oil that may occur due to leakage from the large tank.

Electrical connections between the driving circuits in the cabinet behind the microscope column and the rectifier and filters in the oil tank are made by shielded cables, the oil-tight connections into the oil tank are made by means of modified automobile spark plugs fitted in the metal flange of the cover. The oil drum, which is mounted under the reservoir, is connected through a valve to the bottom of the large tank. This second reservoir is used to lower the level of the oil in the large tank in the event that it is necessary to gain access to the electrical equipment inside the tank. Compressed air is used to return the oil to the large tank. High voltage connections to the electron gun of the microscope are made by means of large size aluminum tubing. One intermediate insulating support is used and consists of a cylindrical rod of hard rubber fitted with corona shields.

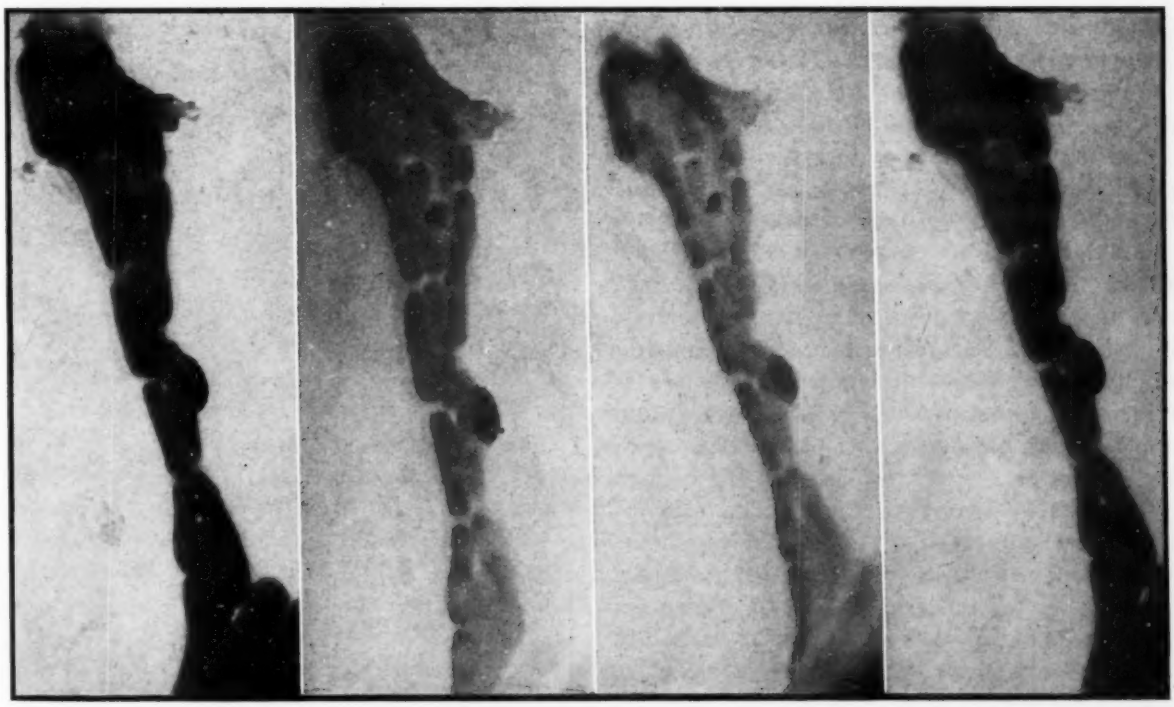
With the exception of the electron gun, the microscope column is essentially the same as that previously described. A two-stage gun has been designed which has been found to operate sufficiently steadily up to 280 kilovolts. The design is such that the central electrode, which is connected to the half potential ring, draws negligible current from the high voltage generator. The projection lens is of a double type that has been used experimentally to obtain large fields of view and high magnifications in the lower voltage instruments. At the time of writing, the objective and condenser lenses have not been modified in any way, although the position of the specimen has been raised to compensate for the increase of focal length of the objective which is obtained at

the higher voltages. At 250 kilovolts the instrument is capable of giving a magnification of 10,000 diameters. A liquid-air trap has been incorporated in the construction of the high vacuum manifold but has been found to have no effect on the final pressure obtained. It has been found to decrease the time required to pump the system to this final pressure after the insertion of a new photographic plate. The remainder of the vacuum system is the same as in the commercial instrument.

A number of problems were encountered in the testing of the instrument. The most serious of these was due to the hard x-rays generated by the instrument at the higher voltages. Above 200 kilovolts x-ray intensities as high as 10^{-3} r/sec. were measured at some points about the instrument. Reducing this to below the safe value of 10^{-5} r/sec. required the extensive use of lead as a shielding material around the gun and in those parts of the instrument where the electron beam strikes metal parts surrounded by thin walls. In order to make the system completely safe for the operator, all the high voltage equipment has been installed in a room which is lined with grounded metal shielding. As the complete unit weighs several tons, it was necessary to reinforce the floor of the laboratory building before the installation of the equipment.

A further and unexpected installation difficulty was encountered in the form of building vibration. The addition of the rather large and heavy electron gun to the standard instrument changed the vibration characteristics of the latter instrument in such a way that it became very sensitive to vibrations transmitted to it from the building or from the normal manipulation of the controls. This trouble was finally overcome by mounting a brace between the intermediate tube of the microscope column and the cabinet at the rear, and by mounting the whole instrument and cabinet assembly on thick pads of sponge rubber. The transmission of vibration to this assembly from the building was prevented by providing all the electrical, vacuum, and water connections to the instrument with flexible couplings.

In operation the new equipment has been found somewhat more difficult to adjust than the



50 kv (a) 200 kv (b) 250 kv (c) 50 kv (d)

FIG. 3. A group of B. megatherium taken with electrons of various velocities. (×5000.) (Preparation by: Dr. K. Polevitzky, University of Pennsylvania.)

commercial unit. This is particularly so at the higher voltages. In order to obtain steady operating conditions above 200 kilovolts it is essential that the insulators in the electron gun be very clean, and that the high voltage conductors be free of large dust particles. It has been found that it is necessary to readjust the instrument completely for each accelerating potential that is used. This is due to: (1) the optimum adjustment of the electron cathode is associated with a slight space charge effect in the cathode region; the magnitude of this effect is dependent on the potential applied: (2) the effects of slight asymmetries in the magnetic field lenses are minimized by compensating adjustments in the aligning process; the magnitude of the necessary compensating adjustments is also dependent on the accelerating potential used. The ultimate resolving power seems to be about the same as the commercial type, although an accurate check has not been made over the whole range of voltages. Preliminary photographs taken with this equipment at 200 and 250 kilovolts show that a resolving power of at least 100A is attainable at these voltages.

While it is not yet possible to describe any quantitative results obtained with the new installation, a few examples of the results that are being obtained can be shown. These demonstrate the increase in penetration obtained with the use of higher accelerating potentials. Figure 2 is a series of micrographs of an ordinary blood smear on collodion. These were taken at 50, 100, 150, and 200 kilovolts. The exposure times of the negatives and the prints were adjusted so that the intensity in the image of the clear space in the specimen is the same in each case. It can be seen how the red cells and the thick material at the lower side of the micrograph taken with 50-kilovolt electrons are completely opaque, while with 200-kilovolt electrons they are transparent. The effect is shown by the image of the edge of the supporting wire which becomes visible at 200 kilovolts. Figure 3(a) is a comparison between a micrograph of B. megatherium taken with 50-kilovolt electrons and the same group of organisms taken with 200-kilovolt and 250-kilovolt electrons. (Figs. 3(b) and 3(c).) It can be seen that a considerable amount of structure becomes differentiated in the inner part of the organisms when it is viewed by the higher voltage electrons. Figure 2(d) is another print from the same negative of the micrograph taken at 50 kilovolts; it is printed light to show that there is no structure in the overexposed portions of the above print. Figure 4 shows one of the first

FIG. 4. Cut section of body wall of a cockroach. Taken with 200-kilovolt electrons (×14,000). (Preparation by: Dr. A. Glenn Richards, University of Pennsylvania.)

satisfactory electron micrographs that has been obtained of a cut section of natural material. It shows the structure in a cut section 1 to 2 microns thick, of the body wall ("skin") of a cockroach, taken with 200-kilovolt electrons.

The preliminary results indicate that the expected increase in penetration is the only advantage obtained from the use of higher accelerating potentials and that this increase in penetration becomes useful only at potentials above 150 kilovolts. There appears to be no advantage in using the high-voltage microscope to examine specimens which are transparent for the lower-voltage commercial instrument.

We wish to thank Mr. J. M. Morgan for his valuable assistance in the design and test of the electrical equipment.

Studies in Lubrication

X. Friction Phenomena and the Stick-Slip Process

F. Morgan, M. Muskat, and D. W. Reed
Gulf Research & Development Company, Pittsburgh, Pennsylvania
(Received June 19, 1941)

Studies have been made of the stick-slip behavior recently investigated by Bowden and collaborators. The friction apparatus consists essentially of a table which can be made to rotate at a very low velocity and a slider elastically supported at the center of rotation of the moving surface. Examples are shown of the stick-slip process with several combinations of metals at various speeds and loads. Motion pictures of the slider and table have been made in order to study possible slipping during the stick phase. Temperature records of the stick-slip cycle indicate that the temperature flash is confined exclusively to the slip period and in no case studied exceeds 50°C above ambient. Traces made of the slip phase with very high camera speeds permit an analysis of the variation of kinetic friction with velocity. Thus both static and kinetic friction data can be obtained from a single stick-slip cycle.

Introduction

WHILE performing experiments on the friction between unlubricated surfaces, Bowden and Ridler[1] observed variations in friction and concluded that the force of kinetic friction inherently may not be constant. In order to make a further study of any possible fluctuations Bowden and Leben[2] constructed special apparatus with an elastic friction measuring element possessing a high natural frequency of vibration. Similarly a high frequency spring system was used for applying the load to a flat plate which could be driven at a slow and uniform velocity by a water piston. Each of the springs had a natural frequency of at least 1000 c.p.s.

When the plate was set in motion the slider was observed to move along as though the two had stuck together until the restoring force of the spring became sufficient to jerk the slider loose and bring it back into position to stick again. During the slip-back portion of this cycle a voltage corresponding to a temperature flash of a few degrees could be observed when the metals were such as to form a thermoelectric junction. However, because of the short duration of the flashes and the shunting effect of parallel couples, it appeared that the actual temperatures might be much higher than the measured values, and melting temperatures were considered to be a distinct possibility. Local welding, as a result of high temperature and plastic flow was thus postulated, and the observed "stick-slips" were explained as being the manifestation of this welding and the subsequent rupture of the contacts.

Previous experience of Bowden and Ridler[1] was introduced as evidence to corroborate their prediction of very high surface temperatures. The method there adopted for measuring the contact temperature was the same as that previously employed by Shore[3] and independently by Herbert[4] for measuring the temperature associated with the cutting of metals. That is, the thermoelectric voltage was determined, preferably by an instrument having a low natural period, and from a previous calibration the temperature of the given couple could easily be ascertained. At high speeds and loads temperatures of several hundred degrees were often observed, the maximum temperature rise in many cases being limited by the melting point of one of the metals. Theoretical evidence was introduced which was supposed to show that temperatures of such magnitudes may reasonably be expected. The calculations lose much of their significance, however, when it is realized that, according to the formula, which was developed on the assumption that the slider was a cylinder of infinite

[1] F. P. Bowden and K. E. W. Ridler, Proc. Roy. Soc. **A154**, 640 (1936).
[2] F. P. Bowden and L. Leben, Proc. Roy. Soc. **A169**, 371 (1939).
[3] Henry Shore, J. Wash. Acad. Sci. **15**, 85 (1925).
[4] E. G. Herbert, Proc. Inst. Mech. Eng **1**, 289 (1926).

length, the temperature varies inversely as the radius of the area of contact, and by assuming a sufficiently small value for this quantity the calculated temperature may reach any arbitrary value. Nevertheless, this work did show directly that if conditions are severe enough, melting temperatures may actually be produced when one metal slides on another. This is exactly the explanation that has been invoked by Bowden and Hughes[5] to explain the formation of the Beilby layer, an amorphous film found on the surface of a solid after polishing. Of course, from a practical point of view these observations are merely a simplified counterpart of those cases of the "burning out" of bearings when the heat generated by friction cannot be dissipated sufficiently rapidly by the bearing housing.

The possibility that the phenomena observed by Bowden and Leben are merely characteristic of the generally accepted properties of friction and of the particular apparatus employed has been pointed out in a number of publications. Thus Blok[6] has shown that such vibrations may simply represent a type of relaxation oscillations which may, in turn, depend upon the particular form of the friction-velocity curve and the amount of damping in the system. The experiments of Papenhuyzen[7] on the skidding of automobile tires have shown that the behavior of the vibrating member may be influenced decidedly by the dragging speed and the load. The resultant motion was found to be either uniform, of a relaxation type, or sinusoidal according to whether the speed was very low, medium or high. The relaxation theory of Blok is in qualitative agreement with some of the main features of these experiments.

As early as 1929 Wells[8] experimented with a machine for measuring friction under conditions of boundary lubrication. The sliding surfaces were flat and parallel and the frictional force was measured by means of a trifilar suspension of weights arranged in such a way that the restoring force increased with the displacement. With highly refined oils alternate sticking and slipping took place under certain circumstances and

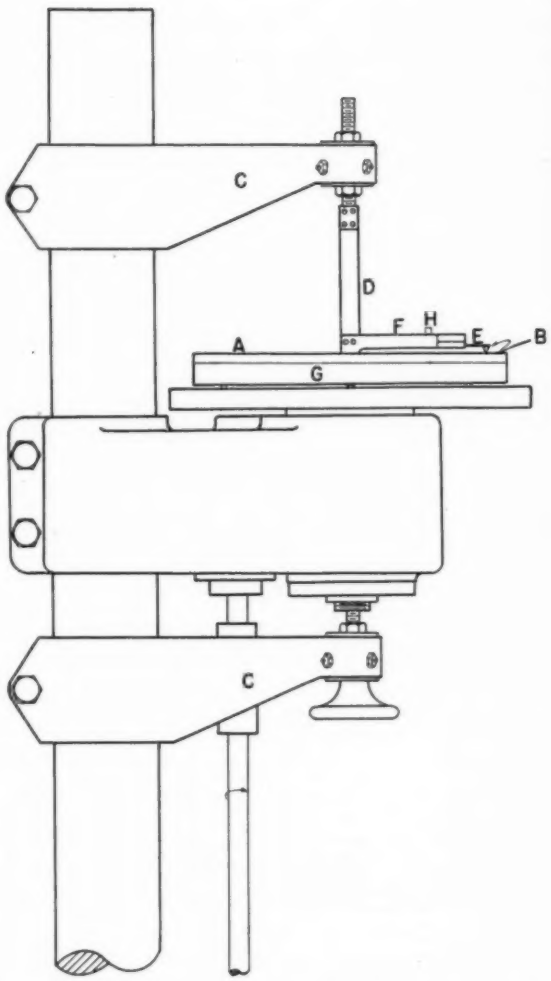


FIG. 1. Schematic diagram of friction measuring apparatus.

steady kinetic readings could not be obtained. "Oily" oils, however, were found to give dead beat readings. No very serious attempt was made to explain the presence of the "unstable region" in which only static measurements could be made, and differences in behavior for different oils were considered to be due to variations in adhesion.

In 1933 Kaidanovsky and Haykin[9] made a study of relaxation oscillations as applied to mechanical systems having friction varying with the velocity. They asserted that a necessary condition for such vibrations is that a region must exist for which the friction decreases as the velocity increases. Under such circumstances

[5] F. P. Bowden and T. P. Hughes, Proc. Roy. Soc. **A160**, 575 (1937).
[6] H. Blok, J. Soc. Aut. Eng. **46**, 54 (February 1940).
[7] P. J. Papenhuyzen, De Ingenieur **53**, 75 (1938).
[8] J. H. Wells, The Engineer **147**, 454 (April 26, 1929).
[9] N. L. Kaidanovsky and S. E. Haykin, Zeits. f. tech. Physik **3**, 91 (1933). See also S. Haykin, L. Lissovsky, and A. Solomonovich, J. Phys. U.S.S.R. **2**, 253 (1940).

equilibrium is unstable. A well-known example of a friction-velocity curve that possesses a decreasing branch, a minimum, and an increasing part is the curve for fluid friction in the region of boundary lubrication. At velocities below the point of minimum friction the curve rises rapidly with decreasing velocity because of thin film lubrication or partial metallic contact, while beyond the minimum the friction is again higher because of an increased rate of shear of the lubricant. In order to test their theory, Kaidanovsky and Haykin performed experiments on a cylindrical journal bearing, for which, as is well known, the above characteristics apply. When the relative velocity was in the region where the friction characteristic was decreasing, oscillations were observed which very closely resembled those obtained by Bowden and Leben.

In performing experiments in which spherical surfaces were made to slide on a well lubricated flat surface, the present writers also observed much the same type of behavior. The torque on three symmetrically located spherical sliders was measured by the twist in a torsion wire which was equidistant from all of the three sliders.[10] Oscillations, which frequently became almost violent, were observed. The behavior was explained, apparently quite satisfactorily, on the basis of the friction characteristic curve. Thus when the relative surface velocity was very low the frictional torque was high because of boundary lubrication conditions, and the sliders were carried along with the moving plate. Finally, however, the torsion in the wire exceeded the frictional force, the surfaces started moving with respect to each other, the force of friction decreased, and the sliders gained momentum as they were pulled back toward their normal position by the torsion wire. A little beyond the position of zero torque the motion was reversed, the sliders were again pulled along with the moving surface, and the entire procedure was repeated.

A. Klemencic[11] has recently examined the mechanics of friction-measuring apparatus and has shown that in the case of fluid lubrication conditions of stable equilibrium prevail, while for mixed or boundary lubrication equilibrium is essentially unstable. Emphasis was placed upon the necessity of taking into consideration the dynamical properties of the system and of applying suitable damping in cases of unstable

[10] The apparatus with which these observations were made was that previously used in the study of the lubrication of flat sliders. (F. Morgan, M. Muskat, and D. W. Reed, J. App. Phys. **11**, 541 (1940).)

[11] A. Klemencic, Forschung Ingwes. **11**, 108 (1940).

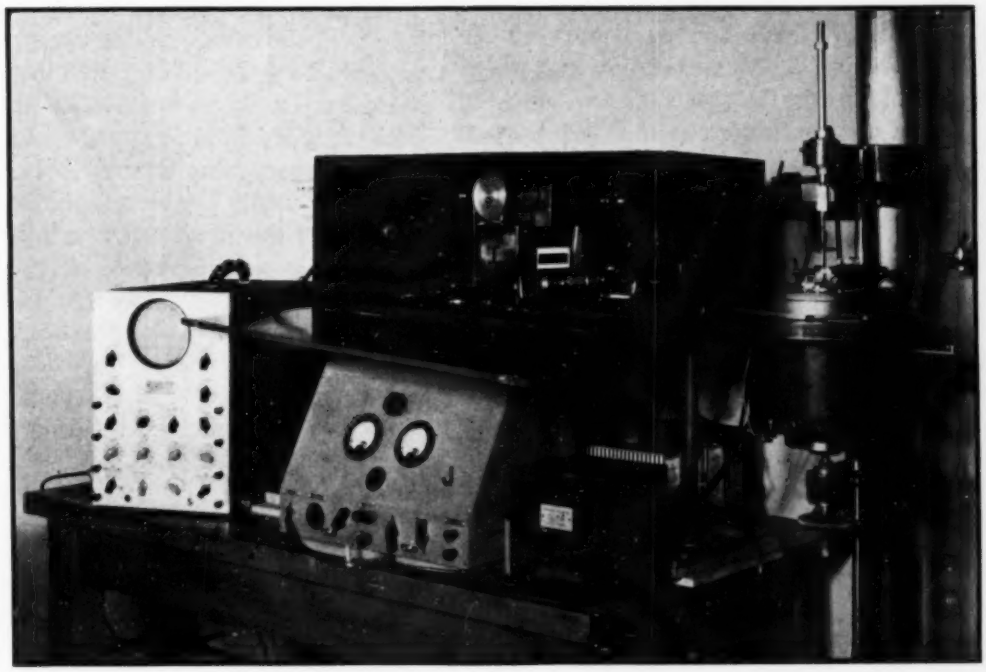


FIG. 2.

equilibrium if usable measurements are to be obtained. The possibility of determining the friction coefficient curve as a function of velocity by utilizing the constants of the system apparently escaped attention.

As experiments of the type described by Bowden and Leben seemed to show considerable promise of being suitable for evaluating the lubricating properties of oils, apparatus was assembled for a further study of the stick-slip behavior.

Apparatus

Figure 1 is a schematic diagram of the essential parts of the slider and friction-measuring mechanism and Fig. 2 is a photograph of the complete apparatus. As far as possible equipment already available has been utilized. The rotating table and gear mechanism are the same as were used previously for experiments on the lubrication of plane sliders.[10] The driving parts (not shown) consist of a single-phase motor, a variable speed transmission and a gear reducer. Track speeds are continuously variable from about 0.003 cm per sec. to approximately 200 cm per sec. Actually, the table speed has not been strictly uniform. While a more uniform motion would unquestionably be preferable, the results indicate that extreme constancy of speed is not indispensable.

The force of friction is measured between the moving surface A (Fig. 1) and the slider B which is connected to the supports C through the elastic friction-measuring element D, the loading spring E, and the rigid member F. The plate G, which carries the moving friction surface, is mounted on three screws to facilitate leveling. The slider support consists essentially of two parts in order that the frequency of vibration of the friction-measuring apparatus may be practically independent of that of the loading mechanism.

The motion of the slider may be recorded by means of a light beam reflected from the lens and mirror combination H onto the moving film of the camera shown at I in Fig. 2. The camera is of the type that has been used in this laboratory in seismic recorders.[12] By using various voltages and gear trains, the speed of the recording film may be varied between the limits of about 0.2 cm/sec. and 600 cm/sec. The recording paper for this particular camera is 70 millimeters wide.

The frequency of the timing lines for reference purposes has been chosen to be roughly proportional to the speed of the sensitized paper. Thus, for the lowest speed, a chronograph has been found to be suitable. At greater speeds, the source has been the power supply, a tuning fork of 100 or 500 cycles, or a vacuum tube oscillator which operates at 1000 or 2000 c.p.s.

Transverse vibrations in the friction-measuring element, which apparently are due to the unbalanced nature of the force on the torsion spring, have been largely eliminated through damping by means of a rubber pad. Damping of the torsional oscillations has been relatively small in all cases. The torsion spring was placed at the center of rotation of the table to prevent as much as possible relative radial motion between the table and slider as the latter is deflected tangentially. In this manner spurious slippage during the stick cycle which occurred when the slider spring support was placed outside the slider-table contact circle was eliminated.

From the description already given of the friction-measuring mechanism it is apparent that this part of the apparatus has been deliberately designed so that the motion of the slider may inherently be of a vibratory character. Load is applied through the spring steel segment E which has a natural frequency in the direction of the load of approximately 1000 cycles per second. This frequency has purposely been made high in order to decrease the time required for the slider to return to the moving surface if, for any reason, contact should be broken. The frequency of the slider in a direction parallel to that of relative motion may be varied over rather large limits by changing the thickness of the spring steel segment D. This method of changing frequency, of course, also involves a change in the sensitivity or deflection of the spring per unit load, but this may, if necessary, be compensated by a change in the length of the path of light. Oscillograms have been obtained (with a slightly different friction-measuring mechanism) for a number of springs for which the natural frequency varies from 45 to 930 cycles per second. By far the greater number

[12] The authors gratefully acknowledge the cooperation of Mr. O. F. Ritzmann of this laboratory in making the recorder, the chronograph, and various pieces of miscellaneous equipment available for these experiments.

of data has been obtained, however, for the spring having the lowest frequency of vibration. This design of the vibrating system has been found to be satisfactory and reasonably convenient as the frequency in the direction of sliding may easily be varied without affecting the frequency in the direction in which the load acts.

In order to find the coefficient of friction, the spring D must be calibrated by applying a known force to the slider in the direction of motion and measuring the resulting deviation of the spot of light on the sensitized film. The force of static friction is then equal to the force required to give the slider a displacement equal to that at which sliding begins. In practice, the displacement of the spot of light for various load increments was photographed and the deflection per unit load was determined from the resulting traces.

The greater part of the error occurring in the determination of the coefficient of static friction undoubtedly arises either in the location of the position of no frictional force or in the measurement of the load. The zero point was found by removing the load from the slider and permitting it to return to its equilibrium position. That this was very close to the true position of zero deflection was demonstrated by the fact that it returned very nearly to the same spot each time during a series of trials. The method of determining the load is open to criticism. The upward force required to just break electrical contact between the slider and the moving surface was measured and assumed to be equal to the load on the slider. Actually this measured force may be expected to be somewhat higher than the actual load for the deflection on the spring will be greater during a measurement by an amount equal to the compression and digging in of the slider. Moreover, small variations in flatness of the moving surface introduce relatively large changes in load.

The coefficient of kinetic friction is not as easily determined as the static coefficient. According to the method adopted by Bowden and Leben it will simply be the value obtained by dividing the force corresponding to the average displacement of the slider by the load. If the conventional definition of kinetic friction is assumed, however, it is necessary to have additional information on the inertia and damping of the moving system. In this paper, stretched out curves of the slip portion of the cycle will be shown, from which it is, in principle, possible to determine the usual coefficient of kinetic friction, but an analysis of the curves will be deferred until a later date.

Little can be said, at present, in regard to the nature and condition of the surfaces which will invariably give rise to oscillations of a definite type. Experiments have been conducted with moving surfaces of tool steel, copper, brass, stainless steel, aluminum, Babbitt and nickel, and with sliders of constantan, steel, copper, tin, zinc, and Wood's metal. The results of only a few typical combinations will be shown, however. Considerable difficulty has been experienced at times in conditioning the surface, as only small amounts of lubricant or abrasive are necessary in order to make the sliding process continuous. Plates have been prepared most successfully by lapping with fine carborundum on cast iron and then finishing with rouge and water, and finally drying with alcohol, or by polishing with fine emery paper and then washing until all traces of contaminant or abrasive have been removed. Most of the experiments on steel were performed on plates having a hardness of approximately 200 Brinell, although oscillations have been obtained for steel of over 500 Brinell. Attempts, largely unsuccessful, have been made to correlate the magnitude of the coefficient of static friction with the occurrence or lack of occurrence of "stick-slips." Thus, while static friction for a surface lapped with fine carborundum was found to be higher than for the same surface when polished with fine emery paper, sliding usually became continuous after a short time in the former case while sustained vibrations were the rule in the latter. It is probable that grit imbedded in the material during the lapping process interfered by collecting between the slider and plate. As a general rule, results are more consistent when at least one of the sliding surfaces is soft than when both are hard. It seems reasonable to expect this behavior as the contact in the former case is more uniform and local variations have less effect. The surface finish has been varied from relatively rough to "mirror smooth" with no appreciable difference in the type of sliding.

No unique explanation has been developed for rapid variations sometimes observed in the values

of the coefficient of static friction. They are probably due to local load variations resulting from a microscopic lack of flatness, as very small changes in level are accompanied by relatively large differences in load. Longer time fluctuations may be due to lack of macroscopic flatness or to variations in surface conditions, as very small quantities of contaminants have large effects upon the results obtained.

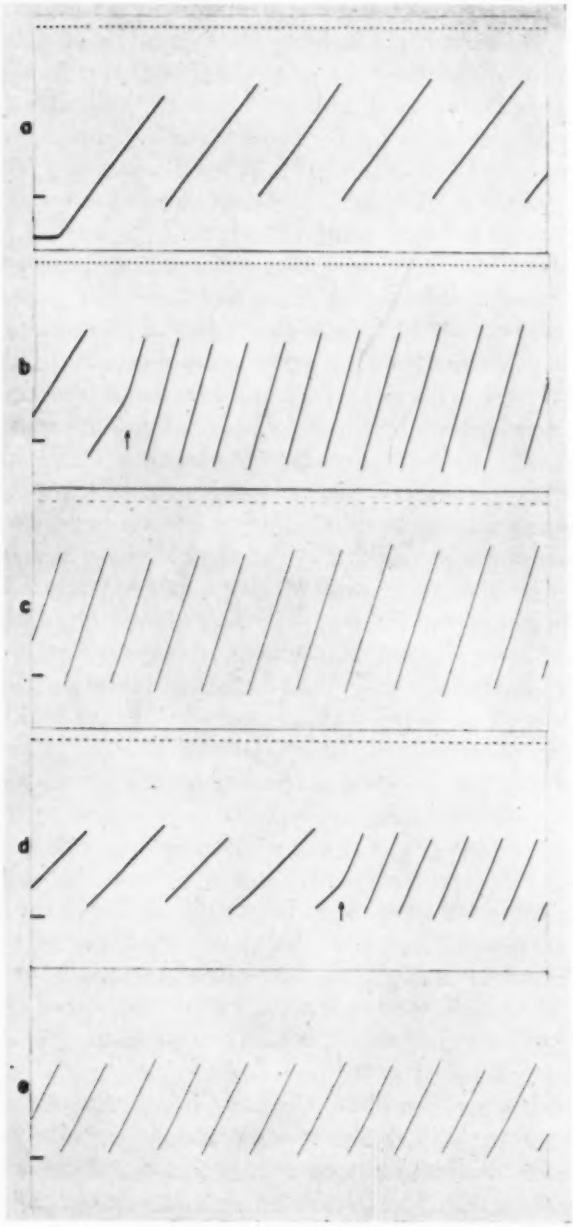


FIG. 3. Wood's metal sliding on Babbitt. (a) load, 400 g; velocity, 0.025 cm/sec. (b) load, 400 g; velocities, 0.025 and 0.060 cm/sec. (c) load, 450 g; velocity, 0.106 cm/sec. (d) load, 250 g; velocities, 0.025 and 0.060 cm/sec. (e) load, 275 g; velocity, 0.106 cm/sec. Timing line frequency, 1 cycle/sec.

For temperature measurements a constantan slider has usually been used in conjunction with a steel or brass plate. Electrical contact was made directly to the steel plate at low speeds and through a mercury cup at high velocities. The use of a return lead to the plate is necessary as fluctuating voltages are observed when the ground return is made through the gears and other elements of the machine.

As the oscillograph elements which have high natural frequencies of vibration also have low sensitivities, it was necessary to amplify the thermal voltages before they could be recorded. For this purpose a d.c. amplifier *J* was constructed.[13] It consists essentially of two stages of amplification, using 1603 and 6SJ7 tubes, and an output stage of three twin-triode tubes in parallel for matching impedances. The maximum voltage amplification of the first two stages is about 5000, but because of the low resistance output the total gain is only about 200.

In order to render small changes in contact resistance between the slider and moving surface as ineffective as possible, a high amplifier input resistance is desirable. On the other hand, when this resistance is high, difficulty may be experienced due to changes in contact resistance affecting the grid potential of the first tube. An input resistance of 5000 ohms has been found to be suitable. Precautions taken in this selection were largely unnecessary, however, as separate measurements indicate that the resistance between slider and plate is never greater than a fraction of an ohm.

Most d.c. amplifiers are subject to considerable drift unless special precautions are taken, and this one is no exception. Microphonics and various electrical disturbances proved to be troublesome at all times. Only by taking extreme care was it possible to reduce the objectionable features to the extent that they introduced no serious difficulties. An a.c. amplifier would undoubtedly be more stable, but the d.c. instru-

[13] We are indebted to Mr. Gary Muffly of this laboratory for the design of the amplifier. The method of coupling successive stages is due to Dr. W. M. Brubaker of the Westinghouse Research Laboratories.

ment possesses a fidelity of response at low frequencies that is rather difficult to obtain in an a.c. device. Moreover, the equipment chosen has the decided advantage in the present case, inasmuch as it will respond to a steady e.m.f. arising from a temperature that has reached an equilibrium value. This characteristic is of little importance at very low sliding speeds where the heat is dissipated during the slip time, but at high speeds an increased average temperature is to be expected and has actually been observed.

The thermal e.m.f. *vs.* time curve may conveniently be viewed and recorded simultaneously by using a cathode-ray oscilloscope in conjunction with the recording oscillograph element. As the sensitivity of the available cathode-ray tube with its built-in amplifier is about 30 r.m.s. millivolts per inch with no attenuation, pre-amplification must be provided. The voltage gain of 200, available through the d.c. amplifier, is quite sufficient to bring the generated e.m.f. within the range of the oscilloscope. The oscilloscope, together with its amplifier, does, however, give an indication of an upper limit to the thermal voltage generated during the return of the slider toward its equilibrium position. The maximum value, as estimated in this way, is substantially in agreement with the value indicated by the recording oscillograph.

Experimental Results

Photographs of typical traces for Wood's metal sliding on Babbitt are shown in Figs. 3(a), (b), (c), (d), and (e). The loads were 400, 400, 450, 250, and 275 grams, respectively. The velocity of the moving surface was approximately 0.025 cm/sec. for Fig. 3(a) and the portions of the film to the left of the arrows in Figs. 3(b) and 3(d), 0.060 cm/sec. for the parts to the right of the arrows in Figs. 3(b) and 3(d), and 0.106 cm/sec. for Figs. 3(c) and 3(e). Reference marks in all cases had a frequency of one cycle per second, but the camera speed was varied as indicated by the spacing of the lines.

The position of zero force on the slider is indicated by the short horizontal line at the left of each figure.

In each case, if the slope of the straight portion of the stick line is compared with the table speed, it is found that the slider was pulled along with the moving surface until the restoring force of the spring became sufficient to pull it back. A very rapid slip then occurred, to be followed by the slider again adhering to the table. The change in slope in Figs. 3(b) and 3(d) is in good agreement with the change in speed of the moving plate. The first stick has been reproduced in Fig. 3(a) to show its resemblance to the others of that particular series.

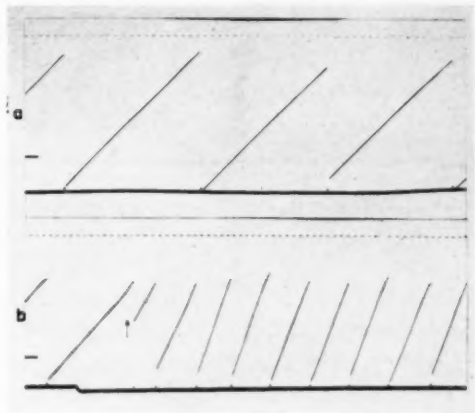


Fig. 4. Constantan sliding on brass. (a) load, 525 g; velocity, 0.025 cm/sec. (b) load, 375 g; velocities, 0.025 and 0.060 cm/sec. Timing line frequency, 1 cycle/sec.

The coefficient of static friction, as determined by the average maximum displacement of the slider from its equilibrium position, was about 0.8 in each of the first three examples. At smaller loads the curves show much the same characteristics, but for some materials the coefficient of static friction seems to depend to some extent upon the load. Thus, in the last two figures, where the load was smaller, the average value was about 1.0. These numbers are not, in any sense, to be regarded as the ultimate values for Wood's metal on Babbitt. The lack of uniformity in the maximum displacement of a given series is sufficient evidence of the importance of the role played by the surfaces themselves. Actually each stick and slip cycle may be regarded as a separate experiment in itself.

Figures 4(a) and 4(b) show the results obtained for constantan sliding on yellow brass. The velocities were 0.025 cm/sec. in Fig. 4(a) and 0.025 and 0.060 cm/sec. in Fig. 4(b). The loads were 525 and 375 grams, and the coefficient of

friction about 0.7. The frequency of the timing lines was again one cycle per second.

Figure 5 is for constantan sliding on steel. The load was approximately 625 grams and the

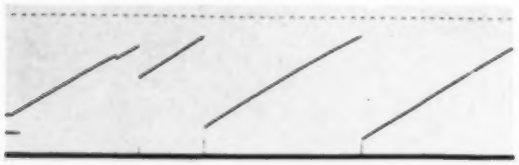


FIG. 5. Constantan sliding on steel. Load, 625 g; velocity, 0.025 cm/sec. Timing line frequency, 1 cycle/sec.

coefficient of static friction about 0.6. The short slip, which occurred during the first period, is an example of an irregularity that has been found to occur much more frequently when both surfaces are hard materials than when either component is a soft metal. Differences in the type of sliding are undoubtedly responsible for the changes observed. The softer metals flatten out more when under load and consequently make more intimate and regular contact. The short slips in Fig. 4(b) seem to contradict these observations, but sliding of the type shown in Fig. 4(a) is more typical of the behavior of brass with other metals in general.

The bottom line in Figs. 4(a), 4(b) and 5 shows the variation of the temperature of the sliding junction. Temperature jumps or flashes occur only during relative motion, as may be expected, and the upper limit of the indicated value for the examples shown here is about thirty degrees centigrade above the surrounding temperature. The magnitude of the observed temperature rise has been found to depend upon the metals comprising the junction, the load, the velocity of the table, and the characteristics of the friction-measuring element. However, in none of these experiments at low table velocity has a temperature flash of more than 50 degrees centigrade above ambient been observed. High temperatures are, of course, produced even at moderate loads when the velocity of the moving surface becomes so large that the heat generated during relative motion cannot be removed as fast as it is generated.

Experiments made with steel sliding on steel and with steel on nickel are convincing evidence that the voltages produced are actually due to thermal effects at the sliding junction. No galvanometer deflections were observed with the like metals. Deflections produced when steel slides on nickel, however, have been found to be opposite in direction from those for constantan on

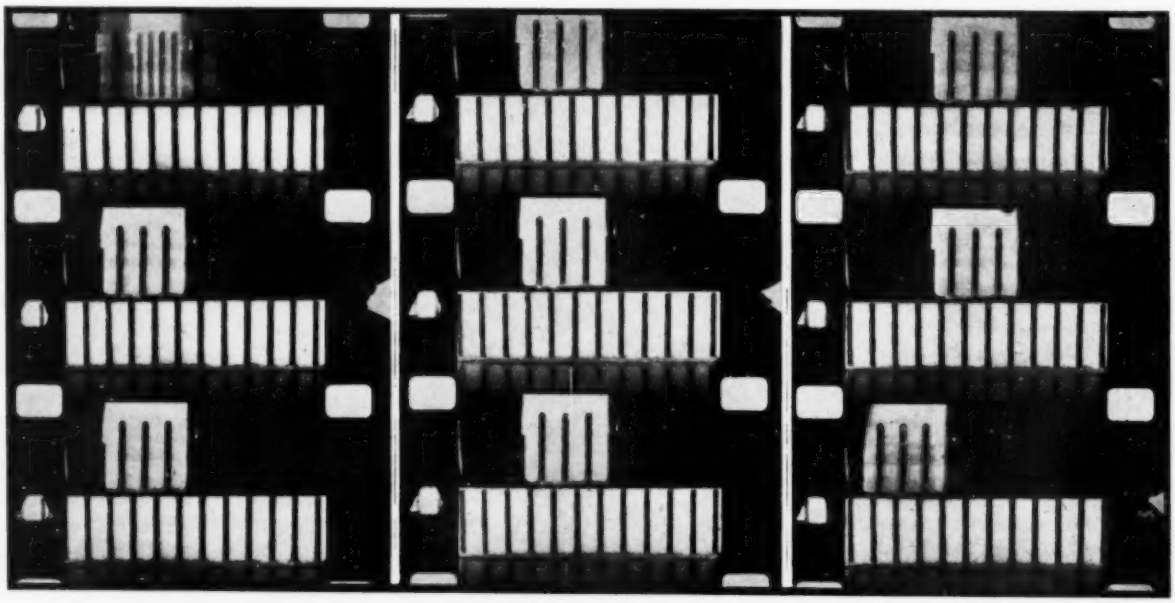


FIG. 6. Motion picture frames showing motion of slider and table. Double exposures of first and last frames show slider positions before and after slip. Materials: steel on Babbitt.

steel. This behavior is in accord with the fact that constantan is negative with respect to steel, whereas steel is positive with respect to nickel.

Conductivity measurements, which have been made of the sliding contact during motion, show that the resistance between the plates and slider is always much less than one ohm. As the input resistance of the amplifier has invariably been very much greater than this value, it is evident that small variations in contact resistance will have practically no effect on the indicated temperatures. Bowden and Tabor[14] had previously arrived at the same conclusion as the result of a more detailed study. It may be noted that these and similar conductivity observations serve to show that the slider does not leave the table during the slip phase but remains in contact with it at all times.

Drift of the amplifier was unusually large in Fig. 4(b). The sharp drop in the temperature line at the left of the figure accompanied a resetting of the zero line.

As measurements of the velocity of the moving surface, the slope of the line on the moving film, and the ratio of light beam deflection to slider deflection involve quantities that are somewhat difficult to obtain with precision, motion pictures have been taken of the sliding process in order to determine whether or not the slider and driven member actually move together during the stick period. To do this, millimeter scales were mounted on the slider and table in such a manner as to eliminate parallax and pictures of approximately actual size were taken. The amount of relative motion or slip could then be measured with a comparator. Figure 6 shows three sections taken at the beginning, middle, and end of the 62 frames obtained during a single stick period for steel sliding on Babbitt. A slip-back occurred during the exposure time of the first and last frames. Measurements have shown that in this case the distance moved by the slider cannot differ from the distance moved by the plate by as much as one percent.

In Figs. 3, 4 and 5 the velocity of the moving film was always very small with the result that the backward motion of the slider, if recorded at all, appears to be practically instantaneous. As an insight into the behavior of the coefficient of kinetic friction as a function of velocity can be obtained in these experiments only by an analysis of this portion of the cycle, it obviously was necessary to modify the experimental technique so as to obtain good traces of the slip even at the expense of the stick line. A stretched-out slip curve for Wood's metal sliding on Babbitt is shown in Fig. 7. The load in this case was 250

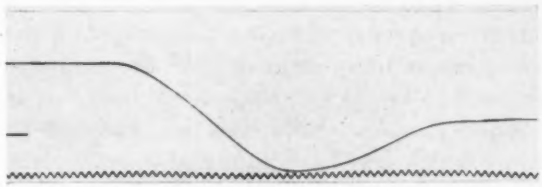


FIG. 7. High speed slip trace for Wood's metal sliding no Babbitt. Timing frequency, 2000 cycles/sec.

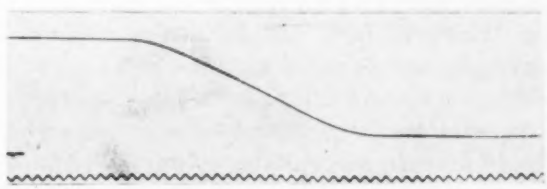


FIG. 8. High speed slip trace for constantan sliding on steel. Timing frequency, 2000 cycles/sec.

grams; the timing line frequency was 2000 cycles/sec. The coefficient of static friction, again determined just before the slider began to slip, was slightly greater than unity. A rather low coefficient of kinetic friction is indicated by the fact that the slider passed through its position of equilibrium before coming to rest. This criterion alone is not enough to determine the kinetic friction, however, as the initial stick displacement, the moment of inertia of the moving system, and the amount of damping must be taken into consideration. Figure 8 shows a similar trace for constantan sliding on steel. In this case the slider did not return to its neutral position before sticking. The coefficient of static friction was lower than for Wood's metal on Babbitt, but the average coefficient of kinetic friction was undoubtedly greater than for the other metals because the slider was picked up again by the moving plate before reaching its position of equilibrium.

[14] F. P. Bowden and D. Tabor, Proc. Roy. Soc. **A169**, 391 (1939).

Discussion

As a result of the observations and experiments to which references have already been made,[1,2] Bowden and Leben concluded that "discontinuities in motion are inherent in the sliding of metals," that "kinetic friction may, with important reservations, be regarded as a series of static frictions." They further state, in regard to their apparatus, "It is clear that a system of this type is capable of recording any changes in the tangential force between the surfaces provided that the frequency of these changes is not greater than the natural frequency of the measuring system."

While Bowden and Leben adopted the procedure which may have appeared to be necessary in order accurately to follow rapidly fluctuating quantities, it is apparent that they neglected to consider the dynamics of their measuring system.*

They have proposed a new theory to replace the "classical laws" of friction according to which, for unlubricated surfaces, kinetic friction is less than static friction. To test this new theory, however, they have constructed apparatus which should perhaps serve better to examine the old. For on the basis of the customary concepts of static and kinetic friction the motion of the slider should be somewhat as follows. First, the slider moves along with the plate and at the same velocity. This will be the situation immediately after the plate first begins to move or just after a slip has taken place and the slider has again attained the velocity of the moving surface. During this part of the cycle there is no relative motion as the force of static friction exceeds the restoring force of the spring. Second, the restoring force of the spring exceeds the force of static friction and sliding begins. After this a knowledge of the shape of the friction-velocity curve is required if the resulting motion is to be predicted. Such curves are not yet available.[15] However, depending on the nature of this variation and the dynamical constants of the apparatus, the slider may swing back past the kinetic friction *vs.* restoring force equilibrium and return with a velocity equal to the table speed and be picked up again for another stick cycle, or it may slide back aperiodically to a constant kinetic friction equilibrium displacement.

It appears, therefore, that Bowden and Leben have ascribed properties to kinetic friction that in reality belong to their particular apparatus. The temperature flashes which occur only during the slip are to be expected and are due to dissipation of energy at this time. Melting temperatures are ordinarily not reached although they may readily be attained if the rate of generation of heat is large due to high speeds or high loads, if the melting point of one of the metals is very low, or if heat cannot be conducted away as fast as it is generated. Nor is melting necessary to establish the stick-slip behavior. This is evident from the fact that the slider sticks to the moving plate in the beginning, that is, before the very first slip occurs and consequently before any temperature flash takes place.

Finally, it should be noted that all the results reported in this paper refer to the sliding of unlubricated surfaces. Experiments are in progress for the study of lubricated surfaces by the present method and apparatus. Results of these investigations, together with those on the analysis of the slip process will be described in a forthcoming paper.

The authors are indebted to Dr. P. D. Foote, executive vice president of the Gulf Research & Development Company for permission to publish this paper.

* As already indicated in the introduction, this observation is not new (references 6, 9, 11). Kaidanovsky and Haykin discussed the case in which friction decreases with velocity, while Blok assumed a constant coefficient of kinetic friction which was always less than that for static friction.

[15] A number of experimenters have presented evidence that friction may vary with velocity other than in the normally accepted manner. Thus Claypoole ("Lubrication" (Texas Co. Bulletin) **24**, 144 (1938)) has observed that with some oiliness agents in conjunction with particular metals friction before sliding begins is less than during motion. W. G. Beare and F. P. Bowden (Phil. Trans. Roy. Soc. **A234**, 329 (1935)) have suggested that some of their experiments may indicate an increase of the coefficient of kinetic friction with a decrease in velocity.

Elastic Aftereffects and Dielectric Absorption in Glass

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Taylor and Doran have found that in stabilized glasses the total elastic adjustment under a given load may be represented as the sum of several terms of the type $l=l_0e^{-kt}$, and have drawn the conclusion that there are several sizes of complex silicate ions in glass which respond independently and with different rates to applied stress.

Hopkinson proposed that there are several independent "elements" responding to the application of an electric field to a glass condenser, and von Schweidler showed that the anomalous charging current accompanying dielectric polarization is the sum of several terms of the type $i=Ae^{-t/T}$. This expression is identical in form with that for elastic polarization if the rate constant k is replaced by a characteristic relaxation time constant $1/T$. The dielectric phenomena thus appear to support the concept of independently acting ions in glass. This idea is in harmony with the x-ray evidence of a random ionic network, and with other physico-chemical evidence.

An interpretation of memory phenomena such as reversal effects in glass and rubber has been offered. Such reversals appear to be due to the superposition of two or more independent operations with different rate constants and directions.

INTRODUCTION

OUR knowledge of the ionic and molecular structures of silicate glasses has been well established as a result of x-ray diffraction studies of simple glass compositions and of silicate minerals. According to W. L. Bragg[1] the unit of structure in crystalline silicates is the SiO_4 tetrahedron in which each Si atom is surrounded by 4 O atoms and held to them by a very strong bond, partly ionic and partly covalent. The whole unit would, if isolated, carry 4 negative charges, but in a crystal these charges are neutralized either by cations such as Fe^{++}, Mg^{++}, Na^{+}, Al^{+++}, or by sharing of common oxygen corners between adjacent tetrahedra so that the over-all atomic ratio Si/O is increased. The ratio Si/O determines the extent of sharing of tetrahedral corners. Thus when $Si/O=\frac{1}{3}$, continuous chains or rings are formed; when $Si/O=1/2.5$, sheet structures such as the micas are produced; and when $Si/O=\frac{1}{2}$, a 3-dimensional network such as that of quartz or tridymite is formed.

Crystals are characterized by a repeating pattern of atomic packing so that when the unit cell is fully described the internal geometry of the whole crystal is understood. On the other hand, the glassy or vitreous condition is characterized by a random, non-repeating network. Nevertheless, silicate glasses do have regularity in the sense that the SiO_4 tetrahedron is again a recognizable feature, as shown by x-ray examination.[2] These tetrahedra, in glass, are connected either firmly by sharing of common oxygen corners or more loosely by linkage through large cations which are usually of low valence. While in silicate crystals the distance between a given Si atom and its nearest or next nearest Si neighbor is a constant, in glass this distance may have any value, within limits, the value depending on the position in space which one SiO_4 tetrahedron may chance to have with respect to another tetrahedron. The consequence of this is that the glass may be looked on as a collection of relatively stable ion clusters or "molecules" of various sizes consisting essentially of groups of SiO_4 tetrahedra rather firmly linked as rings, chains, sheets, or 3-dimensional networks, which may temporarily break away from the rest of the mass by dissociation or rupture of the weaker ionic bonds $Na^{+}-O^{=}$, $K^{+}-O^{=}$, $Ca^{++}-O^{=}$, etc. Such rupture is known to occur during viscous flow or during elastic deformation. These various "molecules" or ionic units will respond to external forces such as tension or electric fields with varying speeds, depending on their size and shape and on the strength and number of the bonds which hold them in place. Kinetic phenomena such as the elastic response or the dielectric absorption should, therefore, be described

[1] W. L. Bragg, *Atomic Structure of Minerals* (Cornell University Press, Ithaca, New York, 1937).

[2] B. E. Warren, "X-ray determination of the structure of liquids and glass," J. App. Phys. **8**, 645–654 (1937).

by a summation of terms in which each molecule has its characteristic constants.

The purpose of the present paper is to present a quantitative treatment of elastic aftereffects and of dielectric absorption in silicate glasses and to show that the experimental data are in complete harmony with the structure of glass described above. The theory would appear to be applicable to any highly viscous system where both strong and weak bonds are present. Incidentally, a simple explanation is found for some peculiar "memory" effects which glass and rubber can exhibit.

It is of interest that some of the leading physicists of the eighteenth and nineteenth century, notably Benjamin Franklin, 1748, Wilhelm Weber, 1835, H. Kohlrausch and L. Boltzmann, 1876, and John Hopkinson, 1876–97, have studied these aftereffects. A satisfactory interpretation could not be forthcoming, however, until more was known of the molecular structure of glasses and liquids.

Delayed Elastic Effects[3]

It has been shown by Taylor and Doran[4] that the elastic elongation of a glass rod or fiber under a constant tension may be represented quantitatively by the expression

$$E_t = I(1-\exp[-k''t]) + l_0'(1-\exp[-k't]) + l_0(1-\exp[-kt]), \quad (1)$$

where E_t is the elastic elongation at time t, I, l_0' and l_0 are constants having the dimension of length, k'', k', and k are characteristic rate constants, and exp (e) is the base of natural logarithms. Figure 1 shows a plot of E_t *vs.* t,

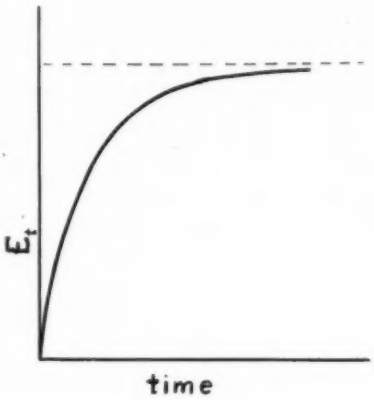

Fig. 1. Elastic elongation as a function of time.

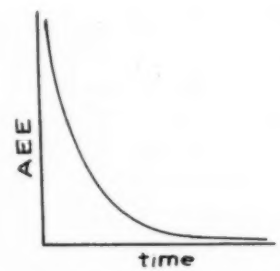

Fig. 2. Available elastic elongation in glasses as a function of time.

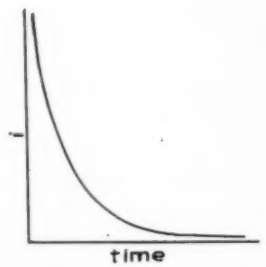

Fig. 3. Anomalous charging current in glass dielectrics as a function of time.

corresponding to Eq. (1). This expression may be rearranged in the form

$$[I\exp(-k''t)+l_0'\exp(-k't)+l_0\exp(-kt)] = [I+l_0'+l_0]-E_t = \text{constant}-E_t. \quad (2)$$

If the rate constants k'', k', and k are replaced by $1/T''$, $1/T'$, and $1/T$, respectively, where T'', T', and T are corresponding elastic relaxation times, Eq. (2) may be written

$$[I\exp(-t/T'')+l_0'\exp(-t/T')+l_0\exp(-t/T)] = \text{constant}-E_t. \quad (3)$$

The expression in brackets may be called the available elastic elongation AEE at time t. A typical plot of AEE *vs.* t is shown in Fig. 2.

The summation of terms in Eq. (3) is a consequence of the postulate that when a piece of

[3] W. Kuhn ["Elasticity and viscosity of high polymers," Zeits. f. angew. Chem. **52**, 289–301 (1939)] has developed a theory of elasticity and viscosity which is similar in some respects to that of the writer. Proceeding in a more or less formal way he generalizes Maxwell's equation to express Young's modulus of elasticity as the sum of a series of terms each of which has the form $E=E_0e^{-t/\lambda}$ in which E_0 is the modulus at $t=0$, and λ is the characteristic relaxation time for the process of elastic adjustment. Kuhn points out that each term corresponds to a given type of molecular binding (Zusammenhaltsmechanism), and that the magnitude of the various λ values, and to a much less degree the E_0 values, determine whether the material will have properties like rubber, steel, glass, etc.

A. Smekal ["The complexity of the freezing (or setting) process in silicate glasses," Zeits. f. physik. Chemie **B48**, 114–118 (1940)] has proposed a similar theory in connection with his work on the strength of glass. He has used data by Taylor and Dear (reference 4) to demonstrate the existence of at least two stages or mechanisms of elastic adjustment and viscous flow in silicate glasses, and to compute the constants characteristic of each stage.

[4] Nelson W. Taylor and Robert F. Doran, "The elastic and viscous properties of several potash-silica glasses in the annealing range of temperature," J. Am. Ceram. Soc. **24**, 103–109 (1941). Cf. also thesis for M.S. degree of R. F. Doran, The Pennsylvania State College, January, 1939.

glass is stretched the different molecular groups in a glass turn individually in such a way as to tend to become aligned with their longest axes parallel to the direction of stretch, and that each kind of group or cluster has its characteristic rate or relaxation time for a given temperature. This theory has been developed on the basis of experimental data obtained by the writer and his students on the elastic behavior in the annealing range of stabilized soda-silica, soda-lime-silica and potash-silica glasses.[5]

Dielectric Absorption

While preparing material, this past semester, for a graduate seminar on the electrical properties of ceramic materials, the writer ran across a stimulating paper by Murphy and Lowry[6] on dielectric absorption, and found there some statements that appeared to relate this phenomenon very intimately with the delayed elastic effects.

When an electric charge is placed upon a piece of glass between condenser plates, the charging current, large at first, decays with time according to the empirical expression $i=At^{-n}$ where n is not an integer and also is not constant for small values of t. This current-time relationship, according to von Schweidler[7] may be better expressed as

$$A_1 \exp(-t/T_1)+A_2 \exp(-t/T_2) + \cdots A_{n-1} \exp(-t/T_{n-1}) + A_n \exp(-t/T_n)=i, \quad (4)$$

where A_1, A_2, A_{n-1}, A_n are constants having the dimensions of current, t is time, T_1, T_2, T_{n-1}, T_n, are characteristic relaxation times of dipoles, and e is the base of natural logarithms.

It is noteworthy that the left-hand members of Eqs. (3) and (4) have exactly the same form and that Figs. 2 and 3 are similar. In Eq. (4) and Fig. 3, the true conduction current has been subtracted, so that i becomes zero when t is large, just as the available elastic elongation becomes zero for large value of t.

The theory advanced by Hopkinson and later put into quantitative form by von Schweidler is that a number of charged elements contribute independently to the anomalous current, according to an expression of the form $i=\text{const. } e^{-t/T}$, where T is a time constant, each element having a different time constant. The summation of the currents due to a sufficient number of elements of this kind can represent the observed results when the constants are properly chosen.

The characteristic rate constants or relaxation times for the various kinds of molecular dipoles are probably determined by the activation energies governing the orientation process. Murphy and Lowry have suggested that ions are adsorbed on materials like cotton and crystalline dielectrics. These ions are held with a wide range of strengths on the inner surfaces or in the Smekal imperfections, and the relaxation time of the ions increases with the strength, i.e., the activation energy of the adsorption. While this theory may indeed be applicable to glass in which "lockerstellen" or Smekal cracks are present, the writer feels that the "random ionic network"[8] of silicate glasses offers a sufficiently wide range of interatomic distances, coordination numbers and electric charge concentrations to meet the needs of the theory. In other words, it does not necessarily depend on imperfections or on surface properties, but is inherent in the random network itself.

The Principle of Superposition—"Memory" Effects

"Hopkinson[9] found that, if a condenser which absorbs a residual charge is charged for some time and then the sign of the e.m.f. is reversed for a shorter time, the first part of the discharge current corresponds in direction to the last charge imposed on the condenser but the direction of the discharge becomes reversed at a later stage of the

[5] Nelson W. Taylor, Edward P. McNamara and Jack Sherman, "A study of the elastico-viscous properties of a soda-lime-silica glass at temperatures near the "transformation point," J. Soc. Glass Tech. **21**, 61–81 (1937). Nelson W. Taylor and Paul S. Dear, "Elastic and viscous properties of several soda-silica glasses in the annealing range of temperature," J. Am. Ceram. Soc. **20**, 296 (1937). Nelson W. Taylor and Robert F. Doran (reference 4).

[6] Edward J. Murphy and H. H. Lowry, "The complex nature of dielectric absorption and dielectric loss," J. Phys. Chem. **34**, 598–620 (1930).

[7] E. von Schweidler, "Studien über die Anomalien im Verhalten der Dielektrika," Ann. d. Physik **24**, 711 (1907).

[8] B. E. Warren and J. Biscoe, "Fourier analysis of x-ray patterns of soda-silica glass," J. Am. Ceram. Soc. **21**, 259–265 (1938).

[9] Quoted from Murphy and Lowry (reference 6).

discharge and corresponds in direction to the first charge." This phenomenon is illustrated in Fig. 4 taken from Guyer.[10]

Lord Kelvin is said to have remarked, "The charges come out of the glass in the inverse order in which they go in," while Hopkinson has stated, "It seems safe to infer that the effects on a dielectric of past and present electric forces are superposable." The explanation offered by Murphy and Lowry is that "the first part of the discharge current is due to layers of ions of small relaxation time, the second to layers of larger relaxation time for which the ionic distribution corresponding to the first charge was not completely effaced by the second charging."

The writer presents curve 1 of Fig. 5 to show the result obtained by addition (or rather subtraction) of two simple exponential curves 2 and 3 where the former has a relaxation time roughly one-tenth of the latter. The reversal in direction of current flow is clearly shown by curve 1.

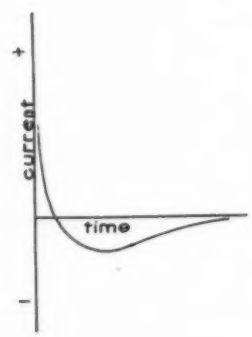

FIG. 4. Reversal in the discharge current from a glass condenser.

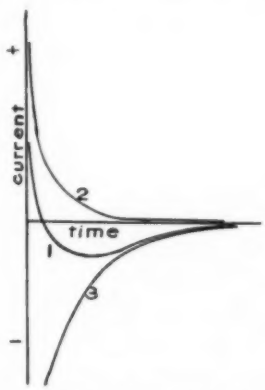

FIG. 5. Reversal in the discharge current, curve 1, shown as the result of two simple discharge curves, 2 and 3, with different relaxation times.

In dealing with these dielectric effects in glass it does not appear to be necessary to use the concept of adsorbed ions, but rather that of weakly or strongly bonded ion clusters in the random network which constitutes the glass. In such a random structure there are small and large "molecules," these being complex silicon-oxygen groups which are separated from other such groups by weak bonds such as $Na^+ - O^=$. Under the influence of an external orienting force the smaller "molecules" would respond more quickly than the larger, presumably because they would have fewer bonds to break as they turn towards the direction of the applied field.

An exactly analogous *elastic reversal* has been observed in rubber[11] in an experiment performed by H. Kohlrausch in 1876 (see Fig. 6). Quoting from Houwink, "A rubber thread, Fig. 6, is twisted $2\times360°$ to the right and held in that position for 18 hours (a). It is then released and twisted 45° beyond the position of equilibrium to the left and held so for 30 seconds (b). An elastic aftereffect is observed first from (b) past the equilibrium to (c), for example, then the direction of the aftereffect is changed and the thread twists to the left until a final position at (d) is reached. The behavior of the thread does indeed give the impression that it possesses a 'memory.'" This behavior again illustrates the intimate relation which exists between the elastic and dielectric effects. Glass, at a suitable temperature, will undoubtedly show analogous elastic reversals.

A simple hydrostatic model illustrating a reversal may be described. In Fig. 7, the central tube is connected to tube *A* by a capillary *S* through which a liquid can flow only slowly, and is connected to tube *B* by a large tube *R* through which flow is rapid. If a suitable volume of liquid is admitted *slowly* into the system through the opening *O*, the level indicated in the central tube will rise from 1 to 2. If, now, the same quantity of liquid is withdrawn *rapidly* from *O*, the liquid level in the central tube will fall first to 3 and then will reverse its direction and rise again to the original level. This analogy shows how a slowly and a rapidly operating mechanism can combine to produce reversals in physical behavior which, on first examination, would appear to be anomalous.

DISCUSSION

It should be mentioned that the anomalous electrical charging currents have, as a rule, been measured on glass at room temperature,[10] while

[10] Cf. J. T. Littleton and G. W. Morey, *Electrical Properties of Glass* (John Wiley and Sons, Inc., New York 1933). Fig. 32, p. 100.

[11] R. Houwink, *Elasticity, Plasticity and Structure of Matter* (Cambridge University Press, 1937), pp. 185, 186.

the delayed elastic effects have been observed on glasses in the annealing range, e.g., 425°C. At these elevated temperatures elastic relaxation times ranging from 1 to 100 minutes were observed. At room temperature the corresponding times would, of course, be very much longer since it is found that the relaxation time is a logarithmic function of the reciprocal absolute temperature. These extrapolated times, therefore, are much larger than those observed for the anomalous charging currents. The explanation probably lies in that the measured electrical effects may correspond to smaller or more rapidly reacting molecules or dipoles than do the measured elastic effects. The difference is one merely of degree rather than of principle, and does not invalidate the essential harmony of the two effects, since dipoles or other polarized aggregates of a very wide range of sizes may be present in glass. In fact, elastic aftereffects have been observed in glass at room temperature[12] and are responsible for the well-known "secular rise of the zero-point of thermometers," an effect which is minimized by suitable choice of glass composition but appears to be characteristic of all glasses.

The intimate relation between the delayed elastic effect and the anomalous charging current in glass becomes evident when it is recalled that dipoles or other unsymmetrical charge distributions are, as a rule, associated with molecules or ions of non-spherical shape, whether of organic or inorganic nature. The application of an electric field will, therefore, tend to displace the electric charges so as to align the dipoles parallel to the field direction. The rate of charge displacement, which is the current, is greatest at first and falls as the dipoles become oriented. Similarly, the application of tension to a glass rod will orient these molecules or ions so that their long axes tend to become aligned parallel to the direction of tension. The rate of elongation due to this orientation is greatest at first, and falls as the orientation approaches completion. Stretching a glass rod or fiber will not produce electrical polarization of the whole piece because of internal compensation between dipoles, but the reverse phenomenon, a kind of Kerr effect, might take place.

[12] G. W. Morey, *Properties of Glass* (Reinhold Publishing Corp., New York, 1938), pp. 316–319.

The delayed elastic elongation has been found to be exactly reversible with the same characteristic rate constants for stretch and recovery.

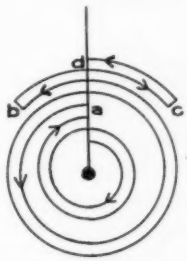

FIG. 6. Elastic reversal *bcd* in a soft rubber rod. Axis of rod normal to page.

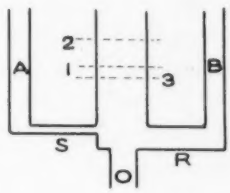

FIG. 7. Hydrostatic model showing a reversal effect.

The anomalous charge current and discharge current are also equal provided correction is made for the true d.c. conduction current. These statements apply to stabilized glasses, i.e., to those in equilibrium with respect to molecular dissociation and association processes, and would apply to non-stabilized glass which is so cold or so rigid that such processes do not occur with measurable rates. The elastic behavior of non-stabilized glasses in the annealing range is more complex since molecular association is taking place at those temperatures. This behavior is described in part by the Adams-Williamson[13] equation for release of strain. Studies of the dielectric behavior of glasses in the annealing range of temperature would be of considerable interest and practical importance.

FURTHER ANALOGIES BETWEEN ELECTRICAL AND MECHANICAL PROPERTIES

When stabilized glasses are subjected to longitudinal tension at constant temperature, the elongation is due to the following elastico-viscous effects: (1) apparently instantaneous, or very rapid, elastic distortion, (2) delayed elastic distortion, and (3) pure viscous flow. The second effect has been discussed in detail, in its relation to the anomalous charging currents characteristic of dielectric absorption. The electric analogy of pure viscous flow is direct-current conductivity[14]

[13] N. W. Taylor, "The law of annealing of glass: Quantitative treatment and molecular interpretation," J. Am. Ceram. Soc. **21**, 85–89 (1938).

[14] Nelson W. Taylor, "Viscosity and electrical resistivity and their bearing on the nature of glass," J. Am. Ceram. Soc. **22**, 1–8 (1939).

and the electrical analogy of the instantaneous or very rapid distortion is the electrical polarization corresponding to the optical part of the dielectric constant, which of course, is determined by the refractive index.[15]

Another point of similarity concerns Young's modulus and its electrical analog. The writer and his co-workers have shown[4] that the ratio stress/strain, or load/elongation is practically constant and independent of temperature for a given glass, when the total elastic elongation (instantaneous plus delayed) is used in the calculation. Similarly, the static dielectric constant (zero frequency) of any rigid dielectric, such as a glass, varies only slightly with temperature. Such variation as does occur appears to be due to the Debye inverse temperature relation, i.e., thermal molecular vibrations oppose the orienting tendency of the electric field. This factor would probably also affect the amount of orientation of non-spherical molecules produced by an external load, and would, therefore, have a small influence on Young's modulus. The explanation for this approximate temperature independence of both the electric and mechanical effects appears to be that if we allow sufficient time for dipole or molecular orientation we should always expect the same amount of orientation for a given electric field or a given external load. In this connection it is worth mentioning that only a small fraction of the total number of dipoles, or molecules, have to be oriented. Debye[16] states that the dielectric properties of ice crystals can be explained by assuming that only one dipole in five million is perfectly oriented parallel to the field, or that all the dipoles are turned an extremely small amount. An effect of this magnitude in glass seems entirely reasonable, without doing violence to our concepts of ionic bond strengths.

[15] P. Debye, *Polar Molecules* (Chemical Catalog Co., New York, 1929), pp. 42, 43.
[16] P. Debye, reference 15, p. 106.

Summary

Elastic and electrical polarization effects are time functions in glasses or other very viscous liquids. The intimate relation between these phenomena is shown in part as follows:

Elastic effects

Maxwell's law for elastic adjustment, $-dl/dt = kl$, in its integrated form is $l = l_0 e^{-kt}$.

Taylor and Doran have found that in stabilized glasses the total elastic adjustment under a given load is the *sum* of several terms of the type $l = l_0 e^{-kt}$.

Dielectric effects

Hopkinson proposed that there are several independent elements responding to the application of an electric field to a glass condenser, and von Schweidler showed that the anomalous charging current accompanying dielectric polarization is the *sum* of several terms of the type $i = Ae^{-t/T}$. This expression is identical in form to that for the elastic polarization if the rate constant k is replaced by the time constant $1/T$.

"Memory" phenomena

Memory phenomena, such as reversal effects, in glass, rubber, and similar substances appear to be due to the superposition of two or more independent operations with different rate constants and directions.

Structure of glass

The elastic and the dielectric evidence lend strong support to the concept that there are several sizes of complex silicate ions in glass, and that these various ionic units respond independently and with different rates to applied stress. This idea is in harmony with other physico-chemical evidence and with the x-ray evidence of a random ionic network.

Determination of Object Thickness in Electron Microscopy

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AND

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(Received June 9, 1941)

It is proposed that the thicknesses of electron microscope objects be determined by measuring the diminution in intensity of the electron beam caused by the object. Since this method would only be applied to specimens so thin that multiple scattering can be neglected, one need know only the total cross section for single scattering of electrons outside the aperture angle of the electron microscope objective. These cross sections are calculated for fast electrons (energies greater than 10,000 ev) by means of the Born approximation for several cases of practical interest, and the results are applied to some experimental observations.

I. INTRODUCTION

THE usual information one can gather about the size and shape of an object by means of an electron microscope concerns the dimensions perpendicular to the optical axis. The determination of the third dimension by means of differential focusing, used in light microscopy, cannot be applied because of the very great depth of focus of the electron microscope. For practical reasons, rotation of the specimen in front of the objective lens cannot generally be realized. In the absence of a specimen with a homogeneous size distribution and random orientation, indirect methods are used for the determination of the third dimension. Throughout this paper we shall call this third dimension parallel to the optical axis the thickness of the specimen. Our purpose is to review the existing methods for its determination and to propose a new one.

Some time ago one of us called attention to the use of accidental curling of a broken collodion film for the determination of particle thickness.[1] Figure 1 is a micrograph of such a curled film with some bacteria shown in profile on its edge. This most direct method is limited however to relatively thick specimens and—since such lucky accidents cannot always be reproduced—to specimens which can be easily placed at an orientation convenient for such observation.

A second method is the stereoscopic one. By taking stereomicrographs at known viewing angles, not only the relative distances of different parts of the specimen in the direction of the optical axis can be measured, but in some cases the thickness too (Fig. 2).[2] As with the first method, its application is limited to relatively thick specimens.

The third method which we propose is to compute the thickness from the measured in-

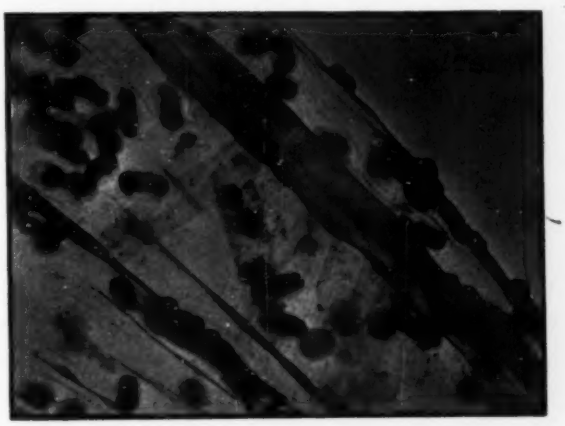

FIG. 1. Whooping cough bacteria on the edge of a curled-up collodium film.

* Now at Stanford University, California.

[1] See T. H. Osgood, J. App. Phys. **12**, 96 (1941).

[2] This micrograph was taken by keeping the object stationary and changing the angle of incidence of the condenser beam, instead of the usual method of tilting the specimen. This could be done because of the relatively large apertures of the electron microscope used for taking these pictures (see also L. Marton, Phys. Rev. **58**, 57 (1940)) and because the image quality is primarily defined by the solid angle of the incident (condenser) beam and not by the actual size of the objective aperture (due to the predominance of large angles in the scattered beam). (See also v. Borries and Ruska, Zeits. f. tech. Physik **19**, 404 (1938).) For stereophotogrammetric measurements see W. Eitel and E. Gotthardt, Naturwiss. **28**, 367 (1940); smallest measured thickness 200A, accuracy ±50A.

tensity distribution of the electronic image. For this purpose let us consider specimens of such thickness that the image formation is due to single scattering alone.[3] For a first approximation it may be assumed that the blackening of the photographic emulsion is proportional to the number of electrons reaching its surface. For a more complete determination, however, either a direct measure of the current in different portions of the image, or a quantitative study of the behavior of the emulsion (for instance, by methods similar to those developed for photographic photometry by Ornstein and his collaborators) may be necessary. Then, if t_0 is the transmission of the negative for a part of the image corresponding to the support, and t the transmission corresponding to object and support, the thickness x is given by

$$x=(1/SN)\ln(t_0/t), \qquad (1)$$

where N is the number of scattering atoms per $\text{cm}^3=N_0\rho/M$, N_0 is Avogadro's number, ρ the density, M the atomic weight, and S is the total cross section for scattering outside the angle limited by the objective aperture. We shall always use ln to indicate the natural logarithm.

II. Theory

We wish to calculate the total cross section for scattering of an electron outside a small angle α, which is the half-angle of aperture of the objective lens of the electron microscope. There are three types of scattering that must be considered: elastic and inelastic scattering by the atom or ion, and scattering by the conduction (free) electrons in the case of a metal. The elastic scattering may be regarded as nuclear Rutherford scattering that is made finite at small angles by the screening effect of the atomic electrons. Since the inner electrons are far more effective in screening the nucleus than the outer electrons, the exact configuration of the valence electrons has little effect on the cross section and we can use results based on isolated neutral atoms even though the atoms are collected together in a solid and may be ionized.

[3] In contrast to a former paper where an estimation of "depth resolving power" was given by considering multiple scattering alone [L. Marton, Physica **9**, 959 (1936)].

The inelastic scattering, on the other hand, is accompanied by excitation or ionization of the atom and so depends markedly on the wave functions of the atomic electrons. As we shall see, the loosely bound outer electrons contribute most to this, so that calculations based on free atoms cannot be regarded as precisely applicable to a solid. We do, however, perform the calculations for free ions instead of atoms where metals or salts of the alkalis or halogens are involved. For organic compounds of H, C, N, O, P, and S,[4] and for "metallic" Sb, in which cases definite ionic structures are not indicated, the best we can do is to calculate for free neutral atoms and assume that the scattering is additive. This is probably a fairly good assumption, since the energy and size of a valence electron state in a molecule are not very different from their values in a free atom.

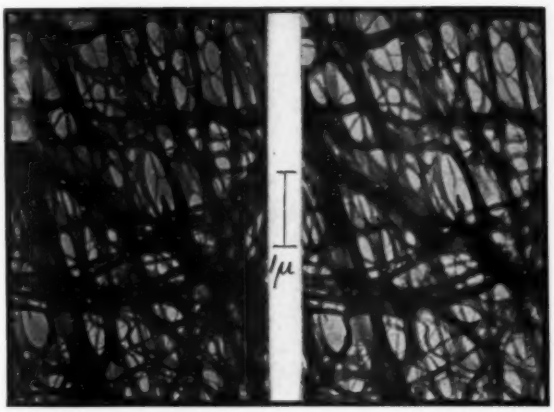

Fig. 2. Stereomicrograph of sodium laurate curd fibers.

The free electron scattering, which, of course, appears only for metals, resembles the elastic scattering in that it is also given by the Rutherford formula. For moderate angles it is $\sim\nu/Z^2$ times the elastic scattering, where ν is the number of free electrons per atom and Z is the atomic number, and is, therefore, negligible. It is, however, important at very small angles, since screening does not reduce it in the same way as the elastic scattering.

Elastic scattering

All calculations will be made for fast electrons with the help of the Born approximation (ener-

[4] F. Seitz, *Modern Theory of Solids* (McGraw-Hill, 1940), p. 72.

gies greater than 10,000 ev), and for small scattering angles θ. It is never necessary to consider large angle deflections, since these are relatively infrequent and contribute a negligible amount to the total cross section if α is small; we can always use the approximation: $\sin\theta \leqq \theta$, $\cos\theta \leqq 1$. The differential cross section for elastic scattering between θ and $\theta+d\theta$ is then given by the relativistic Rutherford formula:[5]

$$d\sigma_e = 8\pi(Ze^2/mv^2\gamma)^2 d\theta/\theta^3, \quad \gamma \equiv (1-v^2/c^2)^{-\frac{1}{2}}, \quad (2)$$

provided θ is larger than the "cut-off" angle θ_1 at which screening of the nucleus by the inner electrons plays an important role. Here, e, m, and v are the charge, rest mass and velocity of the incident electron. For $\theta < \theta_1$, the cross section is roughly constant and can be neglected. Using the Thomas-Fermi model and the Born approximation, one obtains to good approximation:

$$\theta_1 = Z^{\frac{1}{3}}c/180v\gamma. \quad (3)$$

For the lighter atoms, where the Thomas-Fermi model is not a good approximation, we use the numerical computations based on Hartree wave functions quoted by Mott and Massey;[6] because the Born approximation is used here, θ_1 is still proportional to $1/v\gamma$, that is, to the reciprocal of the momentum. We thus obtain on integration of (2):

$$\sigma_e = A(\hbar/mv)^2, \quad \alpha < \theta_1;$$
$$\sigma_e = 4\pi(Ze^2/mv^2\gamma\alpha^2)^2, \quad \alpha > \theta_1; \quad (4)$$

where $\hbar$ is Planck's constant divided by 2π. Here $A = 22Z^{4/3}$ for all except the lightest atoms, and is given in Table I for several cases of practical interest. For most microscopes, α is less than θ_1.

Inelastic scattering

The inelastic scattering cannot be calculated as accurately as can the elastic scattering. We give formulas here which are certainly of the correct order of magnitude, and are probably no less accurate than the assumption that the atomic cross sections are additive in the solid state. It is fortunate that the most doubtful parameter of this calculation appears only inside a logarithm, so that the computed result is insensitive to its choice.

[5] N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Oxford, 1933), p. 88.
[6] Reference 5, p. 124.

Mott and Massey[7] give for the differential cross section for excitation of an atom:

$$8\pi(e^2/\hbar v)^2 |\sum_{s=1}^{Z} (x_s)_{0n}|^2 d\theta/\theta, \quad (5)$$

where we have kept only the dipole term and have replaced their matrix element x_{0n} by $\sum_{s=1}^{Z} (x_s)_{0n}$ for a many-electron atom. Equation (5) is valid for angles in the range $\theta_2' < \theta < \theta_3'$, where:[7]

$$\theta_2' = (E_n - E_0)/mv^2\gamma^2, \quad \theta_3' = (2|E_0|/mv^2\gamma^2)^{\frac{1}{2}}; \quad (6)$$

E_n is the energy of the atom in the state n and E_0 is its energy in the ground state. Summing (5) over all excited states of the atom, we obtain:

$$d\sigma_i = 8\pi(e^2/\hbar v)^2 [(\sum_{s=1}^{Z} x_s)^2]_{00} d\theta/\theta, \quad (7)$$

where the limiting angles (6) can be expressed approximately in terms of a mean excitation energy I of the atom:

$$\theta_2 = I/mv^2\gamma^2, \quad \theta_3 = (2I/mv^2\gamma^2)^{\frac{1}{2}}. \quad (8)$$

Although the contribution to the scattering is negligible outside the limiting angles (8), the large angle deflections contribute a significant amount to the stopping power and have to be considered in calculating it.

TABLE I. *Parameters appearing in Eqs. (4), (8), and (10), A and B are dimensionless numbers, and I is given in ev.*

	A	B	I		A	B	I
1 H	7.3	13.3	13.5	17 Cl^-	930	76	77
2 He	10.6	8.8	38	18 A	875	55	110
3 Li^+	60	3.4	98	19 K^+	1110	43	140
6 C	246	35	44	20 Ca^{++}	1200	33	180
7 N	229	28	63	29 Cu^+	1950	91	130
8 O	209	23	83	35 Br^-	2520	120	130
9 F^-	274	26	91	37 Rb^+	2700	88	170
10 Ne	215	18	130	47 Ag^+	3720	200	170
11 Na^+	316	13	180	51 Sb	4150	220	180
13 Al^{+++}	547	7.5	300	53 I^-	4370	180	150
15 P	840	80	63	55 Cs^+	4600	120	230
16 S	846	70	74				

The matrix element in (7) is readily evaluated if one assumes that the ground state of the atom can be described by an antisymmetric product of

[7] Reference 5, Chapter XI, especially Eqs. (39), (38), (13), (7). The relativity modifications can be established by the method of impact parameters: E. J. Williams, Proc. Roy. Soc. **A139**, 163 (1933).

one-electron wave functions:

$$[(\sum_{s=1}^{Z} x_s)^2]_{00} = \sum_i (x^2)_{ii} - \sum_{i \neq j} |x_{ij}|^2 \equiv (B/4\pi)(h^2/me^2)^2, \quad (9)$$

where i and j represent occupied one-electron states of the atom. On integrating (7), we finally obtain for the total inelastic scattering cross section:

$$\sigma_i = B(h/mv)^2 \ln (2/\theta_2), \quad \alpha < \theta_2;$$
$$\sigma_i = B(h/mv)^2 \ln (2\theta_2/\alpha^2), \quad \theta_2 < \alpha < \theta_3. \quad (10)$$

σ_i is negligible compared to σ_e for $\alpha > \theta_3$; in practical cases, α is less than θ_3. The quantity B has been calculated using Slater wave functions,[8] and I has been estimated as the average binding energy of the individual electrons, weighted according to their contribution to B. The results are collected in Table I for several cases of practical interest. The second part of (9), which subtracts out the contribution from forbidden transitions, is relatively unimportant, except within a shell of given total quantum number. The first part of (9) is just $Z/3$ times the mean square radius of the atom, and is thus a multiple of the diamagnetic susceptibility of the atom. Now it has been found that the experimental susceptibility is given much better by Slater wave functions than by Hartree wave functions or the Thomas-Fermi model.[9] This indicates that, although the latter solutions hold better for the inner electrons, which contribute little to B, the Slater functions are fitted semi-empirically to give good agreement with sizes and energies, especially for the outer electrons. The quantity I is much more difficult to estimate; this is not a serious source of error, however, because of the logarithmic dependence of σ_i on it.

It should be remarked that the velocity dependence of (4) and (10) is much more certain than the computed values of the parameters A, B, and I. Thus these parameters may eventually be determined experimentally with greater accuracy than given here.

Experimental evidence for inelastic scattering at small angles has been obtained by Kuper,[10] and the agreement with theory in the cases of helium is satisfactory.[11]

Free electron scattering

In a metal, the free conduction electrons also contribute to the scattering. This can be calculated using the Rutherford formula (2), with $Z=1$.[12] However, it must be remembered that because of the degeneracy of the electron gas (departure from degeneracy can be neglected at ordinary temperatures), only those electrons that would be knocked out of the occupied sphere in momentum space can cause scattering. The momentum transfer in a given collision is $p=mv\gamma\theta$, so that a fraction $(3p/4P - p^3/16P^3)$ of the electrons take part in a given collision, where $P=2\pi h(3\nu N/8\pi)^{\frac{1}{3}}$ is the maximum momentum of the Fermi distribution, ν is the number of free electrons per atom and N is the number of atoms per unit volume; for $p \geqq 2P$, all electrons can scatter. The differential cross section per atom is then:

$$d\sigma_f = 8\pi\nu(e^2/mv^2\gamma)^2(3\theta/4\theta_4 - \theta^3/16\theta_4^3)d\theta/\theta^3, \quad \theta < 2\theta_4; \quad (11)$$
$$d\sigma_f = 8\pi\nu(e^2/mv^2\gamma)^2 d\theta/\theta^3, \quad \theta > 2\theta_4;$$

here:

$$\theta_4 \equiv \theta P/p = (2\pi h/mv\gamma)(3\nu N/8\pi)^{\frac{1}{3}}.$$

There seems to be no reason to expect screening due to distortion of the electron cloud except at very small angles. One should, therefore, integrate (11) from α as a lower limit:

$$\sigma_f = 8\pi\nu(e^2/mv^2\gamma)^2(3/4\theta_4\alpha - 3/8\theta_4^2 + \alpha/16\theta_4^3), \quad \alpha < 2\theta_4; \quad (12)$$
$$\sigma_f = 4\pi\nu(e^2/mv^2\gamma\alpha)^2, \quad \theta > 2\theta_4.$$

For the metals included in Table I, $\nu=3$ for Al, and $\nu=1$ for Cu and Ag.

Multiple scattering

It is of some interest to see at what value of the object thickness multiple scattering sets in and the single scattering cross sections derived

[8] J. C. Slater, Phys. Rev. **36**, 57 (1930).
[9] G. W. Brindley, Phil. Mag. **11**, 786 (1931); F. E. Hoare, Proc. Roy. Soc. **A147**, 88 (1934).
[10] J. B. H. Kuper, Phys. Rev. **53**, 993 (1938).
[11] J. B. H. Kuper and E. Teller, Phys. Rev. **58**, 602 (1940).
[12] See also reference 5, p. 270.

above can no longer be used. It can be shown[13] that the quantity that determines the amount of multiple scattering is $\int\theta^2 d\sigma$. From (7) and (11) it is then clear that the inelastic and free electron scattering contribute negligible amounts

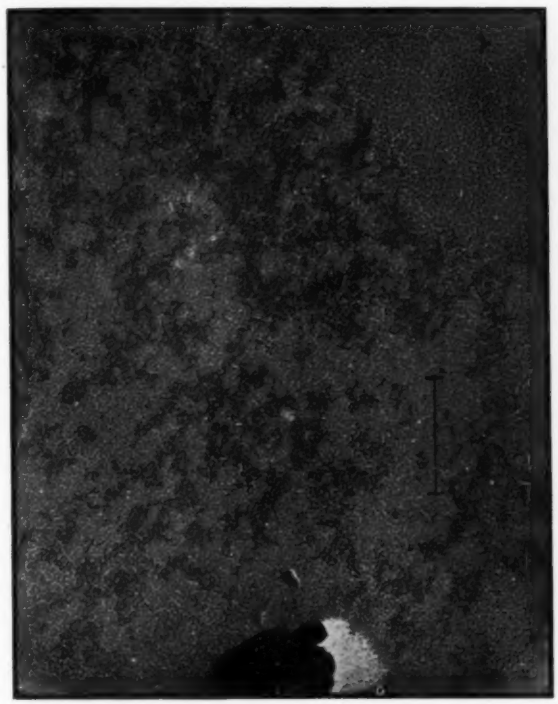

FIG. 3. Thin layer of antimony evaporated on collodion film.

to the multiple scattering. Thus the usual treatment of multiple scattering applies, and one need consider only single scattering so long as the remnant of the incident beam of unit intensity:

$$e^{-SNx}, \quad S\equiv\sigma_e+\sigma_i+\sigma_f, \tag{13}$$

is large compared to the fraction of the multiply scattered beam that enters the aperture:

$$\pi\alpha^2 f(0), \tag{14}$$

where Goudsmit and Saunderson[14] have found:

$$f(0)=(0.43\gamma^2/4\pi D)(v/c)^4 \times(5.60-\tfrac{1}{3}\ln Z+\tfrac{1}{2}\ln D)^{-1}, \tag{15}$$
$$D\equiv 24.8\times10^{-26}Z^2Nx.$$

[13] E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).
[14] S. Goudsmit and J. L. Saunderson, Phys. Rev. **58**, 36 (1940).

Z should be taken as the root mean square average: $NZ^2=\sum_i N_iZ_i^2$. For small thicknesses, the transmitted intensity is given by (13) and for great thicknesses by (14). In between, where (13) and (14) are roughly equal, plural scattering will have to be considered. We omit a discussion of this case since, for applications to electron microscopes, (13) will be the dominant term.

III. APPLICATIONS

A first practical example is the calculation of the thickness of the granules of a thin Sb film on a collodion support as shown in Fig. 3. There have been many proposals to explain the anomalies in conductivity of thin metallic layers by a granular structure.[15] There have, however, been no direct proofs for such a structure. The electron microscope provides such evidence, showing, for instance, that a thin film of Sb is built up of individual granules of approximately 250A diameter. These granules are remarkably constant in their dimensions parallel to the support, and also show a discreteness in thickness. This indicates that the granules grow perpendicular to the support, and may do this in a step-wise manner. The best part of Fig. 3 for measuring the thickness of the particles in a single layer is close to the big dust particle which produced a cast shadow (due to sidewise evaporation). The t_0/t ratio is approximately 1.5. The number of atoms per cm³ for Sb, assuming bulk density for the small particles, is 3.3×10^{22}. With $\alpha=2.4\times10^{-3}$, the total scattering cross section for 75-kv electrons is 3.4×10^{-17} cm². Thus the thickness is 36A. An attempt has been made to check this figure by observing the profile of such an Sb-film on a curled collodion film. The edge appears rippled with an apparent height of the particles of about 50A±20A.

Our next example is in connection with the investigation of the structure of soap curd fibers.[16] Figure 4 represents such curd fibers of sodium laurate $NaC_{12}H_{23}O_2$. As indicated before, we can assume additivity of the atomic (or ionic) cross

[15] See, for instance, E. Perucca, Nuovo Cimento **15**, 365 (1938); J. Strong and B. Dibble, J. Opt Soc. Am. **30**, 431 (1940).
[16] L. Marton, J. W. McBain and R. D. Vold, J. Am. Chem. Soc. **63**, 1990 (1941).

sections and the thickness can be computed from

$$x=(\sum_i S_iN_i)^{-1}\ln(t_0/t). \qquad (16)$$

Here, $N_i = N_0p_in\rho/M$, where N_0 is again Avogadro's number, p_i the fraction of atoms of type i in the molecule, n the total number of

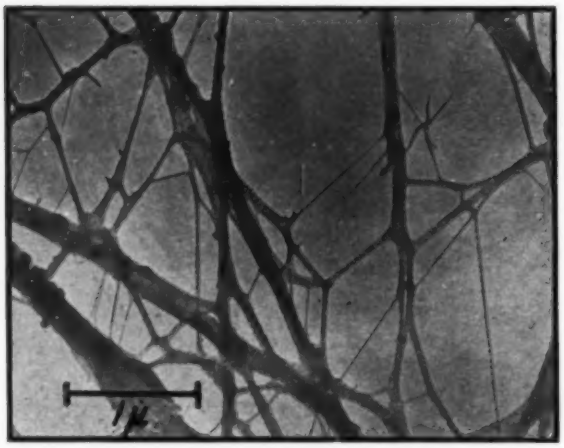

FIG. 4. Sodium laurate curd fibers.

atoms in one molecule (p_in is therefore the number of type i atoms in one molecule), ρ the density and M the molecular weight. The density of the dehydrated sodium laurate curd is 1. The measured value of the t_0/t ratio, from the fibers indicated by arrows on Fig. 4, is 1.20. Thus we obtain for 75-kv electrons with $\alpha=5\times10^{-4}$:

	N_i	S_i	N_iS_i
Na	2.7×10^{21}	2.6×10^{-18}	7000
C	32.4	3.2	104000
H	62.1	0.58	36000
O	5.4	2.5	13000
			160000

$x=115$A.

It may be pure coincidence that other sodium laurate micrographs show a mottled appearance (Fig. 5) with a periodicity of 120–130A.

Another interesting comparison is given by the thin films used as supports for a great number of electron microscope specimens. Different plastics have been used for this purpose, the most common being collodion (mixture of cellulose trinitrate and tetranitrate) and guncotton (cellulose hexanitrate). The thickness of an average good film has been computed by weighting and found to be about 100A. For collodion, t_0/t is observed to be between about 1.1 and 1.2; these give (assuming a mixture of equal parts of tri- and tetranitrate) $x=58$ and 110A, respectively, for $\alpha=2.4\times10^{-3}$, and $x=45$ and 87A for $\alpha=5\times10^{-4}$, at 75 kev.

Among many further interesting applications one more may be mentioned: the application to metallographic specimens. Such specimens cannot be directly observed by actual electron microscopes because there is no true reflection of electrons. On the other hand, a thermionic or a secondary electron microscope does not possess the same resolving power as a high voltage transmission microscope. The obvious way out of this difficulty is to prepare thin replicas of the surface to be investigated and to observe these replicas in transmission. Figure 6 shows an example: the structure of etched stellite reproduced by allowing a drop of diluted gelatin to dry on the surface.[17] The peeled-off gelatin film can either be observed directly or reproduced again by covering the side which was in contact with the metal with collodion solution and dissolving the gelatin after the collodion is dry. Except for shrinkage the replicas reproduce with great fidelity the structure of the surface, and by calculating the thickness of the "ridges" and

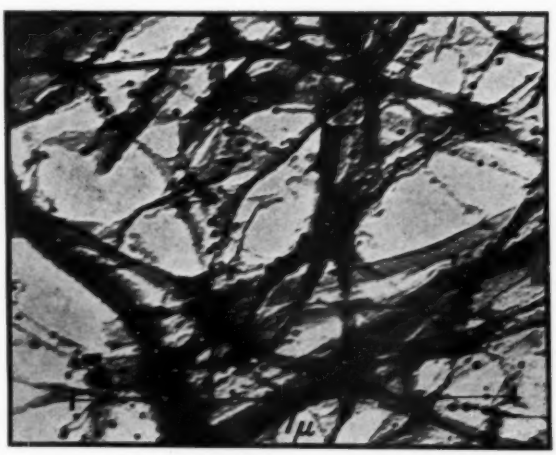

FIG. 5. Sodium laurate curd fibers.

[17] Prepared by Dr. E. G. Ramberg.

FIG. 6. Electron micrograph of stellite structure.

"valleys" of the replica one can get valuable information that is not made available by any other method.

It is worth noting that since α is less than θ_1 and θ_3 in cases of practical interest, the total cross section (except in the case of a metal) is rather insensitive to α, involving it only in the logarithm part of (10). This is illustrated by the computation for a collodion film given above, where a change in α by a factor 5 makes only about 30 percent change in the calculated thickness.

Calendar of Meetings

October

1– 4 Electrochemical Society, Chicago, Illinois
6–10 National Safety Council, Chicago, Illinois
12–15 American Society of Mechanical Engineers, Louisville, Kentucky
13–16 Society of Motion Picture Engineers, New York, New York
15–17 American Society of Civil Engineers, Chicago, Illinois
20–24 American Society for Metals, Philadelphia, Pennsylvania
20–24 American Welding Society, Philadelphia, Pennsylvania
24–25 Acoustical Society of America, New York, New York
24–25 Optical Society of America, New York, New York
24–25 Society of Rheology, New York, New York
30–Nov. 1 Society of Automotive Engineers, Los Angeles, California
30–Nov. 1 National Research Council Conference on Electrical Insulation, Williamsburg, Virginia

November

3– 5 American Institute of Chemical Engineers, Virginia Beach, Virginia
21–22 American Physical Society, Chicago, Illinois

December

1– 5 American Society of Mechanical Engineers, New York, New York
5– 8 National Research Council, Highway Research Board, Washington, D. C.
10 American Standards Association, New York, New York
29–31 American Physical Society, Princeton, New Jersey
29–31 Geological Society of America, Boston, Massachusetts
29–Jan. 3 American Association for the Advancement of Science, Dallas, Texas
29–Jan. 3 American Astronomical Society, Cleveland, Ohio

Innovations in Instruments

New Polarimeter and Polarizing Microscopes

An inexpensive polarimeter is now made available by the Spencer Lens Company of Buffalo, New York. The polarimeter, which functions about the same as a polarizing microscope but provides for the use of liquid instead of solid materials, is designed for teaching polarimetry, for routine laboratory work and for industrial measurements. Elimination of the expensive Nicol prisms through use of Polaroid elements of selected quality, manufactured especially for the Spencer polarimeter, has made possible its low cost and fine performance.

The Spencer Lens Company also announces a series of polarizing microscopes, six new instruments ranging from the usual chemical microscopes to the large research instruments for petrography. All are larger and heavier than past Spencer designs and have new refinements for facilitating observation and measurement of optical phenomena as exhibited by various microscopic materials under the influence of polarized light. These instruments are used in the analysis of crystalline materials or liquids that can be crystallized by evaporating a drop on a microscopic slide, and non-crystalline materials such as starches and fibers. The more complete microscopes have Ahrens prisms for polarizing light; these are made of three wedges of calcite so cut and assembled as to give plane polarized light and maintain a large field of view.

A booklet describing "The use of the Spencer polarimeter" as well as further descriptive material and price lists may be obtained from the Spencer Lens Company, Buffalo, New York.

"Magic Brain"

The Magic Brain, RCA Victor's new automatic record playing mechanism, plays both sides of records without turning them over. This feature, unique in automatic record-changing devices, is made possible by the use of two motors, one to drive the turntable and the other to operate the automatic mechanism. This also makes it possible to increase the capacity of the mechanism to 15 ten-inch records or 12 twelve-inch records. As soon as the Tandem Tone Arm has played both sides of a record it swings free to permit the turntable assembly to tip over to the left, gently carrying the record into the padded pocket below the mechanism. While the turntable is in this position, the next record in the stack drops silently to the heavily felted motor board. The turntable then returns to its original position, raising the record from the motor board en route. While the record is held in position by the record support posts, the turntable spindle seeks out the center hole of the record to be played and finds it, positioning the record for playing. The Tandem Tone Arm is actually two complete Magic Tone Cell pick-ups, set one above the other into a tone arm shaped somewhat like a tuning fork. Its action is completely automatic from the time it leaves rest position at the touch of the starting button until it returns to rest after the last record has been played.

New Sound System

An all-purpose sound system, complete in one compact unit including amplifier, controls and record player, has been announced for use in mobile, portable, or permanent installations by George Ewald, RCA Commercial Sound Division Manager.

The new system operates from 105–125 volts, 60-cycle electric power, or from a 6-volt storage battery with very low drain. It delivers 15 watts output, making it suitable for such uses as in sound trucks, advertising, amusement parks, sport events, political meetings, parades, fairs, carnivals, sales campaigns and picnics.

New Tubes

A new series of vacuum tubes known as Midget Tubes, designed for use at ultra-high frequencies, has been announced by the RCA Manufacturing Company, Inc., Harrison, New Jersey. These tubes are:

RCA-9001, a sharp cut-off pentode intended for use as an r-f amplifier or detector.

RCA-9002, a triode with moderately high amplification factor, useful as detector, amplifier, and oscillator.

RCA-9003, a remote cut-off pentode designed for mixer and i-f or r-f amplifier applications. The super-control features of this tube make it very effective in reducing cross-modulation and modulation distortion over the entire range of received signals.

Ignition Marker of Tubing

An improved patented ignition marker, suitable for aircraft engines and many other applications, has been perfected by the Irvington Varnish and Insulator Company, 24 Argyle Terrace, Irvington, New Jersey. The individual markers consist of lengths of inside and out varnish-impregnated insulating tubing, on which suitable identification is screen printed with a specially formulated ink. Furnished in standardized lengths which are slipped over the wires to be identified, the new markers are available in two diameters (nominal I.D. 0.263 or 0.294 inch).